General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.

- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.

- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.

- This document is paginated as submitted by the original source.

- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

Produced by the NASA Center for Aerospace Information (CASI)



Space Flight with Electric Propulsion

N71-17507
(ACCESSION NUMBER)
(THRU)
(PAGES)
(CODE)
(NASA CR OR TMX OR AD NUMBER)
(CATEGORY)
FACILITY FORM 602

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LEWIS RESEARCH CENTER · CLEVELAND, OHIO · 1969



SPACE FLIGHT with ELECTRIC PROPULSION

Electromagnetic Propulsion Division
LEWIS RESEARCH CENTER *Cleveland, Ohio*
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
1969

CONTENTS

	Page
PROPULSION IN SPACE - FUNDAMENTAL RELATIONS	1
HISTORICAL HIGHLIGHTS	6
ELECTRIC PROPULSION SYSTEMS	9
ELECTRIC THRUSTERS	11
ELECTRIC POWER GENERATION	19
Nuclear-Turboelectric System	20
Nuclear-Thermionic System	22
Nuclear-Magnetohydrodynamic System	25
Solar-Cell System	28
ELECTRIC PROPULSION MISSIONS	30
SERT I	31
SERT II	32
Auxiliary Propulsion	34
Unmanned Primary Propulsion	35
Manned Primary Propulsion	37
OTHER ADVANCED PROPULSION METHODS	41
The Nuclear Rocket	41
The Thermonuclear-Fusion Rocket	43
CONCLUSION	48
APPENDIX - DERIVATION OF ROCKET THRUST EQUATION	49

SPACE FLIGHT WITH ELECTRIC PROPULSION

As man expands the frontiers of knowledge in his exploration of space, his needs for new and highly specialized equipment increase enormously. That he is able to keep pace with these expanding technological needs is evident from many familiar examples. Earth-orbiting satellites, such as the Tiros or Nimbus weather satellites, have taken and transmitted thousands of photographs of the Earth. Communications satellites like Syncom or Early Bird use complex antenna and electronic gear. The Ranger and Surveyor lunar probes and interplanetary probes, such as the Mariner series, are still other examples where special purpose equipment and instrumentation have added to man's knowledge of the Universe. Even more demanding in the requirements for new systems are the manned space flight programs.

Each application, or mission, requires a rocket spacecraft, the main component of which is the propulsion system. Here, too, as the variety of missions increases, a need has developed for propulsion systems capable of specialized functions. This need is easily recognized from comparing the propulsion system requirements to maintain an orbiting satellite at a fixed position in space relative to the Earth with the requirements to send probes to the distant planets like Jupiter or Saturn or to land astronauts on the Moon and eventually on Mars.

Because of this range of propulsion needs, scientists and engineers continually investigate and evaluate new propulsion system concepts. This booklet is about one type of propulsion system that offers promise of filling a wide range of propulsion needs, namely, the electric propulsion system.

PROPULSION IN SPACE - FUNDAMENTAL RELATIONS

Man is accustomed to living and moving about on the Earth's surface. His principal experience with gravitational fields is that things have weight and that falls from heights hurt. Compared with the Earth's gravitational field, the gravitational field in the solar system is complicated. The gravitational field of the solar system can be represented by the gravitational potential as shown by figure 1. This gravitational field may be thought of as a huge circular depression with the Sun at the bottom.

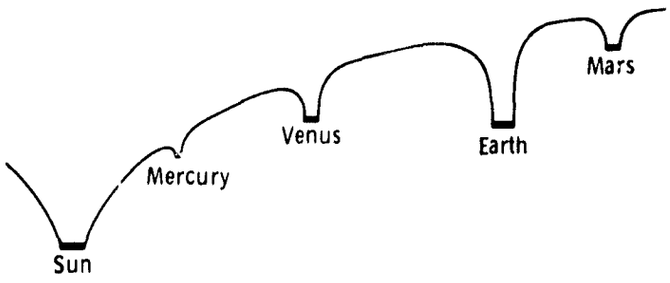


Figure 1.

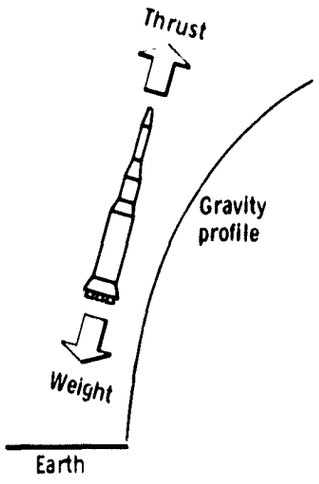


Figure 2.

Each of the planets is located at the bottom of its "gravity depression," which accompanies the planet in its path about the Sun. The gravitational field is quite invisible, but it exerts a decisive force on all objects within its domain. This force is proportional to the slope of the field at the location of the object. In the steep parts of the field, the force is very great, as shown by a sled, which slides the fastest on the steepest part of a snowy hill.

We live at the bottom of a deep, invisible gravity pit, which we must somehow climb out of to reach other planets. There are no ladders, steps, or antigravity machines available; man must propel himself with a rocket spacecraft. If the rocket is to rise directly up the "hill" (gravity profile), its thrust[1] must be greater than its weight (fig. 2). If the thrust is substantially greater than the weight, the rocket will accelerate and pick up speed. If the thrust is applied for a sufficient time, the rocket will pick up enough speed to coast on up the "hill" a little farther. This characteristic can be given a value called total impulse. This quantity is simply the rocket thrust multiplied by the thrusting time:

$$\text{Total impulse} = \text{Thrust time} \times \text{Thrust}$$

Long-distance flights or fast flights require a high value of total impulse. An equation for thrust[2] is

$$\text{Thrust} = \text{Propellant flow rate} \times \text{Exhaust velocity}$$

[1]Thrust is the force exerted by the rocket engine.

[2]This equation is derived in the appendix.

The exhaust velocity is that of the propellant measured relative to the rocket. This expression for thrust may be introduced in the previous equation for total impulse to give

Total impulse = Thrusting time × Propellant flow rate × Exhaust velocity

Finally, thrusting time multiplied by propellant flow rate is equal to the propellant mass at the beginning of the flight, and therefore

Total impulse = Propellant mass × Exhaust velocity

The quantity that results when total impulse is divided by the total propellant weight is known as specific impulse. Specific impulse is proportional to the propellant exhaust velocity and is a measure of the efficiency with which a rocket uses its propellant. In general, the higher the exhaust velocity, the more efficiently the propellant is being used to produce thrust.

Chemical rockets have an upper limit to their exhaust velocity; for this reason, a large propellant mass must be used for flights that require a large total impulse. The electric rocket has a much higher limiting exhaust velocity, with the result that much less propellant is needed. The propellant mass required for a particular space flight (i.e., a particular total impulse) decreases as the exhaust velocity increases, as shown in figure 3.

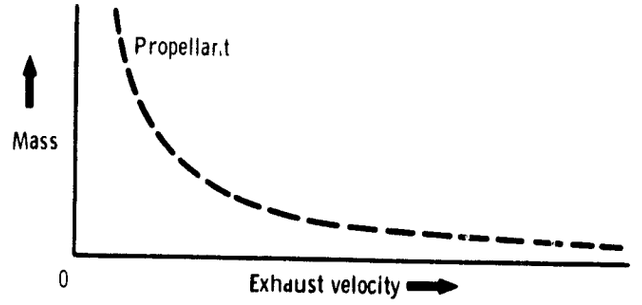


Figure 3.

A fact that is not surprising and that we will examine in more detail in a later section is that electric rockets require electric power. The amount of electric power required increases with increasing propellant exhaust velocity. However, because the mass of the electric powerplant increases if the required power increases, powerplant mass also increases with increasing exhaust velocity, as illustrated in figure 4. Finally,

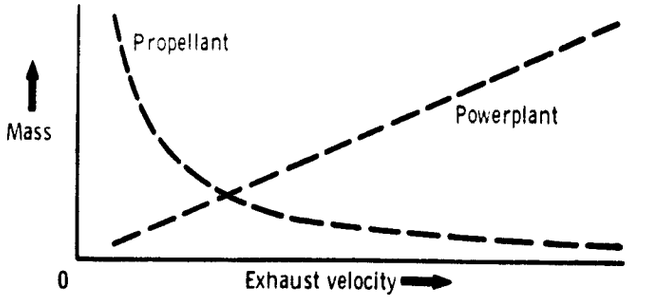


Figure 4.

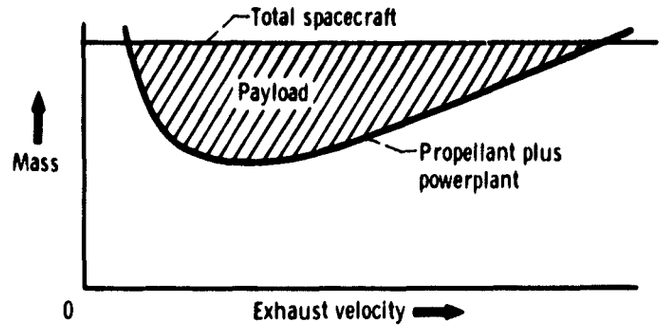


Figure 5.

in figure 5, the sum of the propellant and the powerplant masses is shown as a fraction of the total spacecraft mass. The payload mass is the shaded portion. Figure 5 shows that if the exhaust velocity is less than a certain lower limit, the propellant will be consumed too quickly, and the spacecraft will not reach its destination.

If the velocity is too high, the electric powerplant will have too much mass and the spacecraft can carry no payload. It is evident that the best exhaust velocity to use is that which will allow the most payload to be carried. For electric-rocket trips to the nearest planets, for example, this optimum propellant exhaust velocity is about 30 000 meters per second (67 000 mph).

If a spacecraft is to take off from the Earth's surface, its thrust must be greater than its weight. For such a flight, the electric-rocket thrust would have to be much greater than the weight of the powerplant. The principles described so far can be used to show that extremely lightweight powerplants, for example, of the order of 1/10 000 pound per watt would be required. Thus, a powerplant with an output of 1000 watts could weigh only a few ounces. Space electric powerplants currently under development are hundreds of times heavier than this. Consequently, electric spacecraft currently being studied cannot be expected to take off from Earth. They must be boosted into orbit about Earth by chemical rockets.

Once in Earth orbit, electric spacecraft could propel spaceships effectively with a small thrust. The electric rocket thruster would be started in orbit, and the spacecraft would slowly climb up out of the Earth's gravity pit in a spiral path, as shown in figure 6. Of course, this imaginative diagram only illustrates the principle of slow spiraling away from the Earth's gravitational field. Actually, the spacecraft would follow a spiral path in one plane as shown in figure 7. Since the gravitational field is invisible, it must be imagined in this drawing. As the electric rocket continued thrusting, the spacecraft would continue around the Earth in an ever-widening spiral until it effectively left the Earth's gravitational field. More precisely, it would enter a region in space where the gravity pull of the Earth is slight compared with the gravity of the Sun.

The gravity force of the Sun at the orbit of the Earth is about 1000 times weaker than the gravity force near the Earth's surface. Therefore, even though the thrust

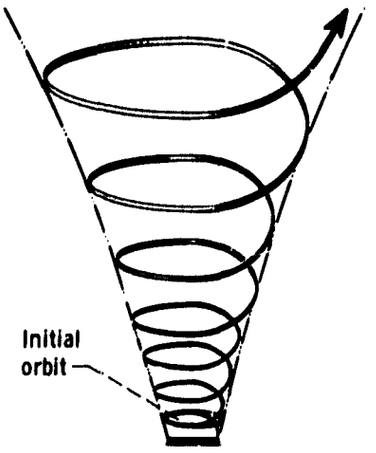


Figure 6.

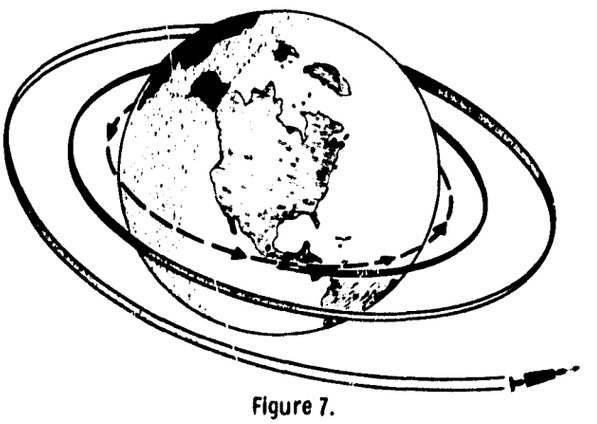


Figure 7.

of an electric rocket is very small compared with the weight of the space vehicle near Earth, the same thrust becomes comparable to the vehicle weight in the Sun's field. This means that, after leaving the Earth's (or other planet's) gravitational field, the electric-rocket-propelled vehicle need not spiral gradually outward but can follow interplanetary paths similar to those followed by high-thrust vehicles.

Thus far almost nothing has been said of the actual speed of a spacecraft. Speed can be a misleading idea in the complex gravitational field of the solar system. For example, if a chemical rocket were to be shot straight up from the Earth's surface, it would have to achieve a speed of about 25 000 miles per hour to escape Earth. It is assumed that the rocket would thrust furiously for a short period, perhaps 15 minutes, and would then coast the rest of the way. The rocket would be coasting up out of the gravity pit, and the farther away from Earth it coasted, the slower it would go. If the gravitational field of the Sun were ignored, the spacecraft would slow almost to a stop far from Earth; that is, it would stop with respect to the Earth. But the Earth moves about the Sun at speeds of nearly 67 000 miles per hour. A spacecraft launched from the Earth also has that speed with respect to the Sun. Furthermore, the Sun is rushing through space; therefore, the spacecraft also has that speed.

Satellite speeds decrease (relative to Earth) as the distance of the satellite from Earth increases. A low-level satellite moving at 17 000 miles per hour takes about $1\frac{1}{2}$ hours to orbit the Earth. The Moon is a satellite of the Earth too. Moving at a speed of about 2300 miles per hour, it takes about 27 days to orbit the Earth. Thus, the Moon, which is at a mean distance of 239 000 miles from the Earth, travels almost eight times slower with respect to the Earth than the low-level satellite.

In a spacecraft hundreds of thousands of miles from Earth, for example, on a

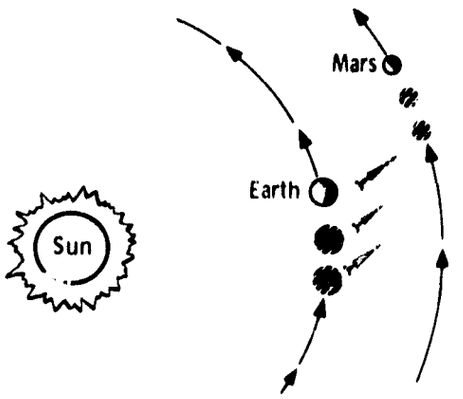


Figure 8.

trip to the planet Mars, the gravitational field of Earth becomes weaker than the gravitational field of the Sun. During the transition from dominance of the Earth's field to dominance of the Sun's field, the spacecraft is attracted to both Earth and the Sun. This situation is so complicated that the spacecraft's path must be calculated on a digital computer even when the rocket is coasting. When free from Earth, the spacecraft still has the speed of Earth with respect to the Sun in addition to its speed with respect to Earth (see fig. 8). Because of its additional speed relative to the Earth, the craft moves farther away from the Sun. As it moves farther away from the Sun, it falls behind Earth in the race around the Sun.

If the spacecraft were on its way to Venus (instead of Mars), its velocity relative to Earth would have to be in the opposite direction, that is, opposed to the Earth's motion around the Sun. The craft would then tend to move inward toward the Sun and toward Venus, which is nearer the Sun than Earth. A tremendous propulsive impulse in a direction opposite to the Earth's motion would be necessary to attain an orbit that passed very close to the Sun, so that there is no danger of inadvertently falling into the Sun.

HISTORICAL HIGHLIGHTS

Rocket-powered spacecraft have the same general function as any transportation system; they move people and materials from one place to another.

Booster rockets are used to launch spacecraft into orbit about the Earth. The high thrust and the comparative safety of chemical rockets make them the only available vehicles for this important first step in space flight. However, as we saw in the previous section, large propellant masses are required for long-distance flights that require a large total impulse. These large masses are necessary because chemical rockets are limited to a low propellant exhaust velocity. Since the chemical combustion process can release only so much energy per pound, the exhaust velocity is limited to about 4000 meters per second.

Several other kinds of rocket-propulsion-system concepts have promise of much higher exhaust velocities than that of the chemical rocket. If these concepts can be made practical, heavy payloads could be carried in long-distance, fast, space flights.



Robert H. Goddard



Hermann Oberth

Dr. Robert H. Goddard, the famous American rocket pioneer, realized that chemical rockets were limited in exhaust velocity. In 1906 he wrote in his laboratory notebook that this limitation in rocket exhaust velocity might be overcome if electrically charged particles could be used instead of burnt gases. Electrically charged particles can be accelerated to extremely high velocities. "Atom smashers" such as cyclotrons can accelerate electrically charged particles almost to the speed of light. The idea of electric propulsion was explored further by Professor Hermann Oberth, a German rocket pioneer. In a 1929 text, Professor Oberth described a possible electric rocket design in which high-voltage electric fields would accelerate charged particles to high exhaust velocities.

The acceleration of electrically charged particles requires a large quantity of electric power. In terms of propellant flow rate, the amount of electric power required is

$$\text{Power} = \frac{\text{Propellant mass flow rate} \times \text{Exhaust velocity}^2}{2}$$

In terms of rocket thrust,

$$\text{Power} = \frac{\text{Thrust} \times \text{Exhaust velocity}}{2}$$

Both of these equations show that electric power requirements increase as the exhaust velocity is increased. Suppose an electric rocket with a 1-pound thrust were to be built. For flights to the nearer planets, an exhaust velocity of 30 000 meters per second (about 67 000 mph) would be best for some electric rockets. More than 66 000 watts of electric power[3] are needed to accelerate enough charged particles to 30 000 meters per second in order to produce 1 pound of thrust. Such quantities of electric power could light thousands of electric light bulbs or run hundreds of electric washing machines.

In the time of Dr. Goddard and Professor Oberth, electric powerplants were very heavy. Today, conventional powerplants are still too heavy for use in electric rocket spacecraft, because they would require large amounts of coal, oil, or gas. Conventional boilers, turbines, and generators would also add greatly to the weight of a self-contained powerplant for space flight. Such powerplants are so heavy and use so much fuel so rapidly that very little payload could be carried.

The advent of practical atomic power wrought a great change in the future of electric propulsion for space flight. As early as 1948, two British scientists, Dr. L. R. Shepherd and Mr. A. V. Cleaver, suggested that controlled nuclear fission could provide the lightweight power source needed for electric rockets. They described an electric-power generation system in which a nuclear-fission reactor would heat a fluid to a high temperature. This fluid would drive a turbine that would drive an electric generator. This generator would, in turn, provide the electricity required to accelerate charged particles to a high exhaust velocity. Small amounts of nuclear fuel can provide very large amounts of power for long times. Although reactor structures and shields were quite heavy when Shepherd and Cleaver first proposed their plan, nuclear-energy technology has advanced rapidly, and their ideas appear more practical today. The development of lightweight nuclear-turboelectric systems for space propulsion power is one of today's most challenging problems. The solution of this problem may be one of the keys to manned interplanetary travel.

Once the theoretical feasibility of electric powerplants for space flight had been

3

$$\text{Power} = \frac{\text{Thrust} \times \text{Exhaust velocity}}{2}$$

and 1 pound of thrust = 4.45 newtons; therefore,

$$\text{Power} = \frac{4.45 \text{ newtons} \times 30\,000 \text{ meters per second}}{2}$$

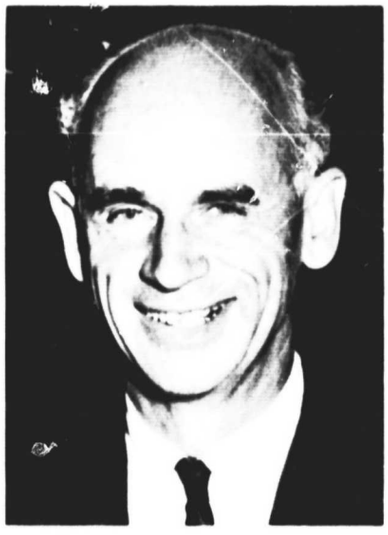
Since 1 watt = 1 joule per second = 1 newton × meters per second, required power = 66 750 watts.



L. R. Shepherd



A. V. Cleaver



Ernst Stuhlinger

established, serious thought began to include another essential part of an electric spacecraft - the electric-rocket engine, or thruster. The first detailed discussion of the electric-rocket engine was prepared in 1954 by Dr. Ernst Stuhlinger, pioneer in electric propulsion. In his papers, Dr. Stuhlinger proposed designs for a cesium-ion engine, which is one type of electric-rocket engine being tested today.

Many researchers have been working on electric propulsion for space flight since 1957. Research on electric propulsion has progressed to the point where electric rocket systems have actually been tested during short-duration space flights. In the next section, we shall examine in greater detail the major components of an electric propulsion system.

ELECTRIC PROPULSION SYSTEMS

Propulsion systems are energy converters. In a chemical rocket, the energy released in a chemical reaction process (combustion) is used to heat the propellant to a high temperature and to eject it through a nozzle to produce thrust. Nuclear rockets use the heat energy from a nuclear reaction process (fission) to heat a propellant and eject it. In most electric rockets, electric or magnetic forces are used to eject the propellant. The electric power needed to produce the electric or magnetic force is supplied by a separate electric power source. In this respect, the electric propulsion system is unique. It is the only type of propulsion system in

which the power source is entirely separate from the thrust-producing element, the thruster. This separation permits an electric rocket to eject propellant at a much higher velocity than chemical and nuclear rockets, thereby achieving much more thrust per pound of propellant. However, despite the greater thrust obtained from each pound of propellant, the total thrust achieved is much less than the weight of the rocket because the required electric powerplant is heavy. Therefore, electric rockets can be used only after the spacecraft has been launched into space by a chemical rocket, and the electric rocket must operate over a much longer time period than either chemical or nuclear rockets. Nevertheless, mission studies show that many missions can be accomplished in periods of time comparable to those of chemical or nuclear rockets and with much less initial weight. In fact, certain missions that are not possible with chemical or nuclear rockets become feasible with electric rockets. As the missions become more difficult in terms of distance to be covered or useful load to be carried, the advantage of electric rockets due to their higher exhaust velocity becomes more and more significant.

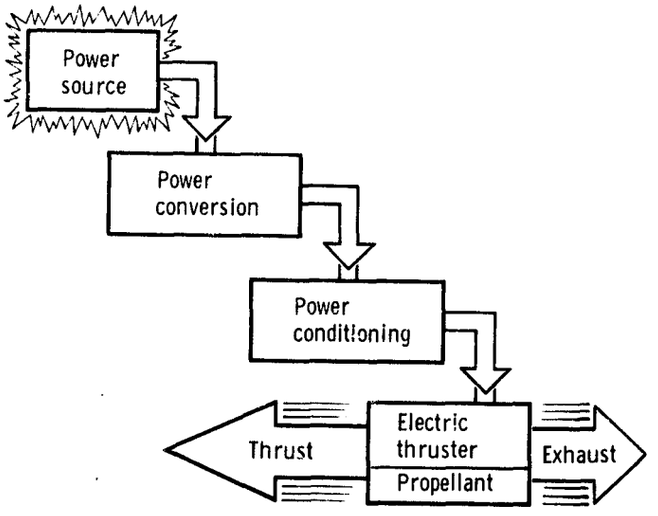


Figure 9.

The main subsystems of an electric propulsion system are shown in figure 9. In the power conversion subsystem, power from the source is converted into electric power. Actually, there are many kinds of power sources and conversion subsystems that might be used with an electric thruster. Some of the most promising types are described in a later section.

In a previous section, we saw that thrust and velocity are related to electric power. A more familiar relation is that

$$\text{Power (watts)} = \text{Volts} \times \text{Current (amperes)}$$

Volts and amperes can be thought of as being similar to "pressure" and "flow rate," respectively. The power conditioning subsystem is used to modify the electrical

voltages and currents (the electrical pressures and flow rates) from the power conversion subsystem to the appropriate levels needed by the thruster, similar to what is done in many household electrical appliances. For example, television sets have components that modify the ordinary household voltages and currents to provide the various values needed to produce the sound and picture. Finally, in the electric thruster, the electric power is used to act on the propellant and produce the required thrust.

This brief description of an electric propulsion system indicates that a wide variety of combinations of the subsystems might be possible. This is indeed true. Many different thrusters and power subsystems are being investigated. It will be easier to understand why these different subsystems are of interest to scientists if we first examine what some of the thrusters are like and how they operate.

ELECTRIC THRUSTERS

The electric-rocket engine, or electric thruster, is a device that converts electric power and propellant into a forward-directed force, or thrust. The general principle of operation is illustrated in figure 10. Electric power is used to accelerate propellant material to a high exhaust velocity. This velocity produces a forward thrust force. By one of the laws of motion discovered by Newton, there must be an equal and opposite reaction for every action. The forward thrust force is the equal and opposite reaction to the rearward exhaust force. The law of action and reaction works in outer space, too, because air is not involved in this principle. Thrust is produced because material is being expelled out of the rear of the engine, not because anything is pushing against air. As a matter of fact, most electric-rocket engines will not work in air; they will work only in a vacuum. Air just gets in the way of the exhaust.

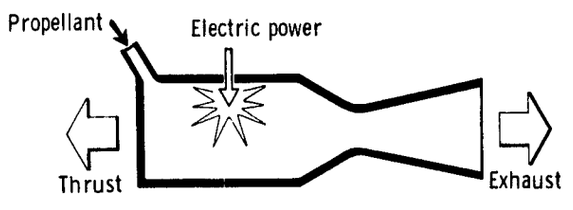


Figure 10.



Figure 11.

The principle of rocket-engine thrust can be illustrated by the following example: A skater stands upright with a bowling ball held near his body. He pushes the bowling ball away. The ball goes flying one way, and he goes flying the other

way (fig. 11). The faster the skater pushes the ball away, the harder he is pushed the other way. Another illustration of this principle is the garden hose. Without the nozzle, the water runs out easily. With the nozzle, the water comes out with a high velocity, and, unless it is held firmly, the hose thrashes about because of the thrust force. All rockets work on this reaction principle.

Electric-rocket thrusters can be divided into three general categories: electrothermal, electromagnetic, and electrostatic. In the electrothermal rocket (fig. 12), electric power is used to heat the propellant to a high temperature. The heating may be accomplished by producing an electric discharge through the propellant gas (arcjet) or by flowing the propellant gas over surfaces heated with electricity (resistojet).

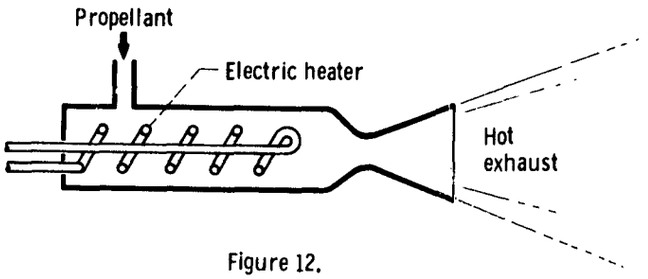


Figure 12.

The electrothermal rocket is similar in some respects to the chemical rocket. Although there is no combustion, the propellant gas is heated to high temperatures and expanded through a nozzle to produce thrust. This rocket can achieve propellant exhaust velocities higher than those of chemical rockets because the energy added to t gas molecules may be larger than the energy available from combustion. Material failure at high temperature, however, places a practical upper limit on the amount of energy that can be added to the propellant. Other factors, such as breakup, or dissociation, of the propellant gas molecules, which absorbs energy without raising gas temperature much, also limit the exhaust velocity.

The resistojet electrothermal thruster is in a fairly advanced state of development. Thruster efficiency[4] of more than 80 percent has been obtained in laboratory tests, and some thrusters already have been tested in space flight. Because the exhaust velocity of the electrothermal rocket engine is limited, it probably will not be used for interplanetary space flight. It could be used, though, for positioning or attitude control of an orbiting satellite.

[4]Efficiency is a figure of merit for electric thrusters. It is a measure of how effectively electric power and propellant mass are used to produce thrust. A thruster with an efficiency of 100 percent would convert all the electric power into thrust by accelerating every propellant particle to the desired exhaust velocity:

$$\text{Electric-thruster efficiency} = \frac{\text{Thrust}^2}{2 \times \text{Propellant flow rate} \times \text{Electric power used}}$$

The second general type of engine is the electromagnetic thruster, often called the plasma thruster. In this thruster, the propellant gas is ionized to form a plasma, which is then accelerated rearward by electric and magnetic fields.

A plasma is an ionized gas, that is, a gas in which electrons have been removed from many of the atoms. In a neutral atom, such as those comprising the incoming propellant gas, there are as many electrons around the nucleus of the atom as there are protons in the nucleus. Neutrons have no electric charge, protons have one positive charge each, and electrons have one negative charge each. With an equal number of positive and negative charges, the atom is electrically neutral. This state is normal for atoms in a gas at ordinary temperatures. If one electron were knocked loose and away from the atom, as illustrated in figure 13 for the helium atom, the atom would have two protons and only one electron. Thus, one excess positive electric charge is left. The charged atom is called an ion. An atom may be multiply ionized by the loss of several electrons.

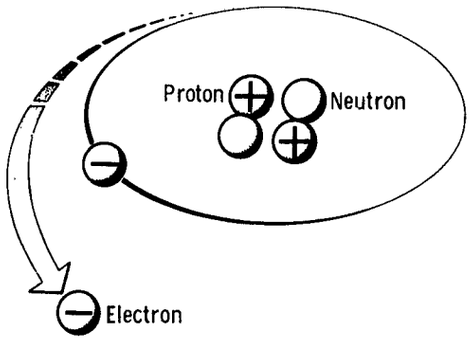


Figure 13.

In a plasma, the electrons and the ions are swirling about in a random manner much like atoms in a gas. The plasma can conduct electric current just as a copper wire can conduct current. It is this conductivity that makes possible accelerating the plasma electrically and magnetically. As shown in figure 14, when an electric current is made to pass through a plasma in the presence of a magnetic field a force is exerted on the plasma. Because of this force, the plasma is accelerated rearward. Thus, a plasma thruster is quite similar to an electric motor with the plasma replacing the moving rotor.

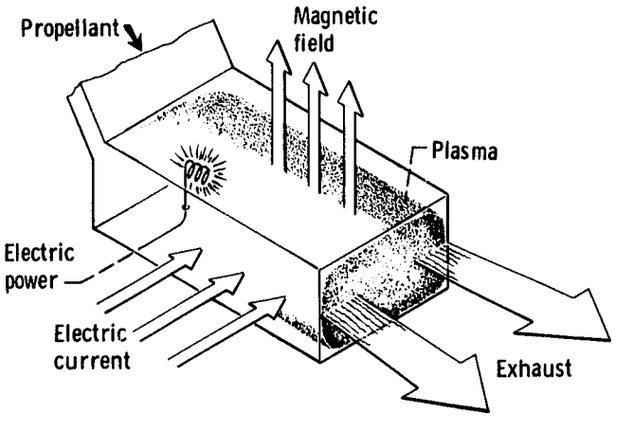


Figure 14.

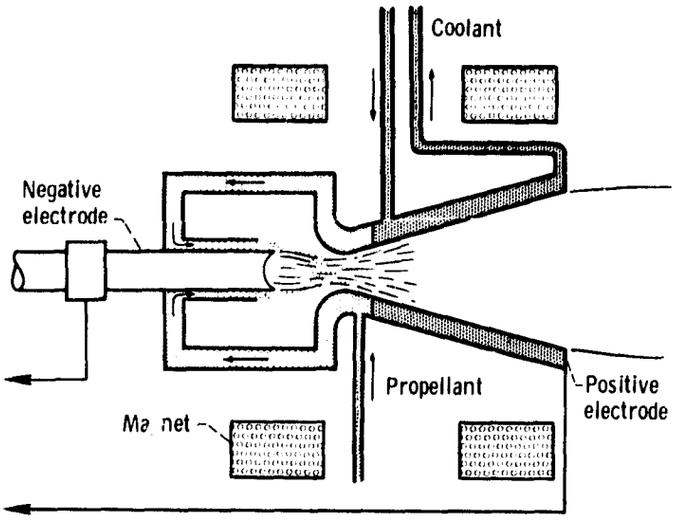


Figure 15.

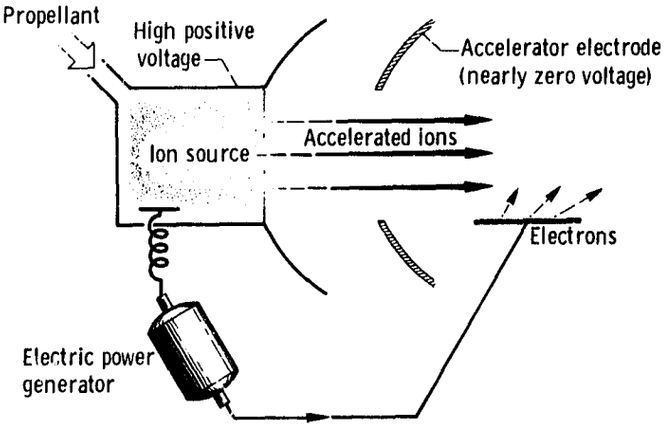


Figure 16.

The MPD (magnetoplasmadynamic) arc thruster illustrated in figure 15 is one of the most promising concepts. This thruster looks like an electrothermal arcjet, but it operates at lower propellant densities where electric and magnetic forces are more important than thermal expansion in generating thrust. The MPD thruster uses a propellant gas, such as hydrogen, ammonia, or lithium, which is ionized to form a plasma and is accelerated rearward. Various thrusters of this type that operate at powers as high as 30 000 watts and produce propellant exhaust velocities of nearly 30 miles per second are presently under study. The MPD thruster is a low-voltage, high-current thruster. It, therefore, has the potential to use solar cell power sources directly with little power conditioning equipment.

The third type of electric rocket engine is the electrostatic thruster (fig. 16). (Best known of this type is the ion thruster or ion engine.) As in the plasma thruster, propellant atoms are ionized by removing an electron from each atom. In the electrostatic thruster, however, the electrons are removed from the ionization region at the same rate as ions are accelerated rearward.

A potential diagram gives a better illustration of how the ions are accelerated (fig. 17). A positively charged particle will always tend to fall down an electric potential "hill." Potential differences are measured in volts. Because the final speed of the ion depends on the height of the potential hill, the exhaust velocity can be con-

trolled by adjusting the voltage of the high-voltage electrode. The ion source is at the same potential (voltage) as the high-voltage electrode. A potential diagram, such as that shown in figure 17, is merely a way of depicting electric fields, which are actually invisible. The electric field exerts a force on particles that have an electric charge. The greater the voltage, the steeper the hill and the greater the force will be.

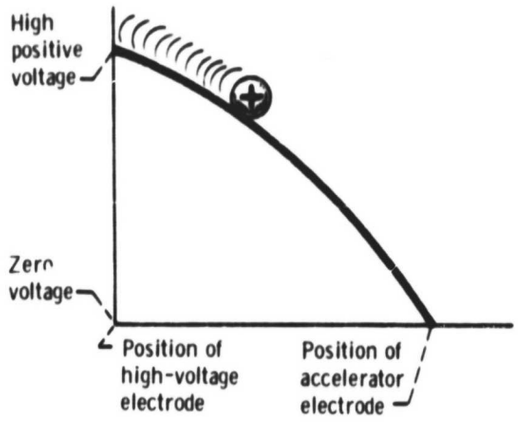


Figure 17.

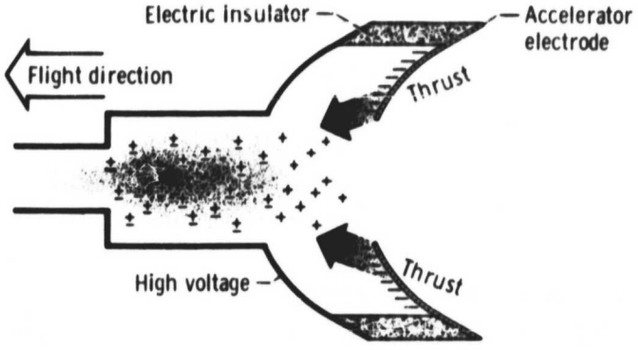


Figure 18.

The electrons freed from the propellant atoms must be removed from the ion source and ejected from the spacecraft in order to maintain the ion source in the electrostatic rocket at a high voltage (fig. 16). The positively charged ions will fall down the potential hill, but electrons have a negative charge and will travel up the potential hill. At the source, the electrons that are freed from the propellant atoms are already at the top of the potential hill; therefore, they must be forced to go down the hill against their natural inclination. Electric power is required for this action. The electric generator is a kind of electron pump that pulls the freed electrons down from the source. Once the electrons are forced down to zero potential, they can be ejected from the thruster. In fact, these electrons must be injected into the ion exhaust beam in order to neutralize the accumulated positive electric charge in the exhaust. If this neutralization were not accomplished, the ions in the beam would stop each other, and a gigantic traffic jam of ions would occur. Without the added electrons the thrust would stop.

The thrust of an electrostatic thruster may be explained in another way. The potential field is produced by surface charges on the accelerator electrode, as shown in figure 18. For the field in the ion engine, these surface charges are negative. The electrostatic attraction between these negative surface charges and the positive

ions rushing through the accelerator results in a force on the accelerator electrode. This force is the thrust in the electrostatic thruster.

The most successful electrostatic thruster presently available is an electron-bombardment thruster conceived and developed by Mr. Harold R. Kaufman, a research scientist at the NASA Lewis Research Center (fig. 19). This thruster operates as follows (see fig. 20): When heated, the propellant evaporates and forms a vapor, which is fed into the thruster discharge chamber. Electron-bombardment thrusters use either mercury or cesium propellant. In the chamber, electrons are knocked out of many of the propellant atoms to form ions. This ionization is accomplished in a gentle electric discharge wherein electrons in the discharge hit electrons in the atom and displace them from the structure of the atom. The



Figure 19.

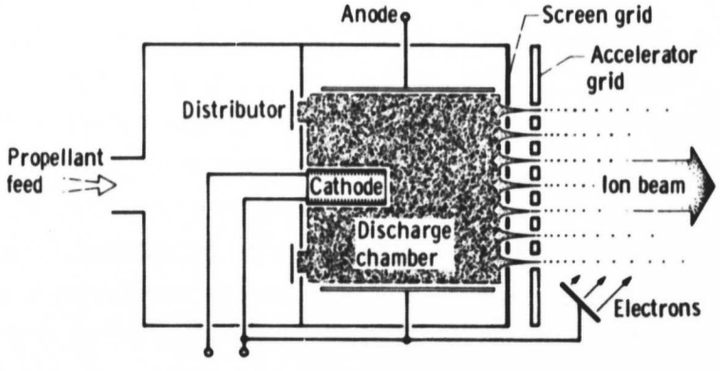


Figure 20.

electrons and the ions form a plasma in the ionization chamber. The electric field between the screen and the accelerator draws ions from the plasma. These ions are then accelerated out through many small holes in the screen and accelerator electrode.[5] Tests have shown that the electron-bombardment thruster can operate at efficiencies near 90 percent.

Another electrostatic thruster of interest is the contact-ionization thruster first proposed by Stuhlinger. In this thruster (fig. 21), cesium atoms are ionized by contact with a white-hot tungsten surface. The electrons taken from each atom are trapped in the porous tungsten. They are removed from the high voltage part of the thruster and expelled into the exhaust in the same manner as before.

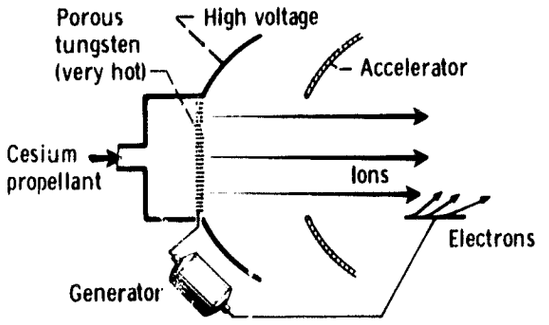


Figure 21.

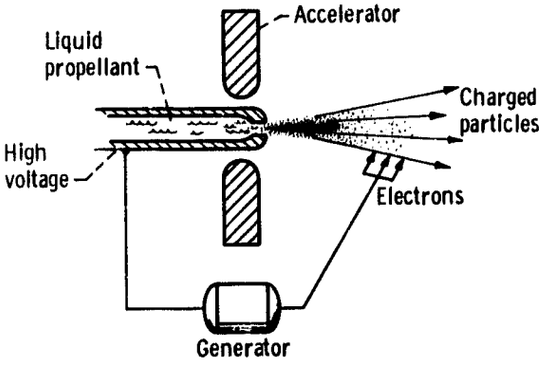


Figure 22.

A third type of electrostatic thruster is the colloid-particle thruster (fig. 22). In one version of this thruster, liquid propellant is fed to the tip of a fine capillary tube which is maintained at high voltage and protrudes slightly through an electrode at near-zero voltage. Electric-field forces charged the tiny drops of propellant as they emerge from the tube tip. Electrons left behind are handled by the generator as before.

Both the contact-ionization thruster and the colloid thruster appear at present to be best suited for applications requiring very small amounts of thrust, that is, amounts less than a millipound (1/1000 of a pound). These applications arise primarily in connection with attitude control of Earth-orbiting satellites. The usefulness of electron-bombardment thrusters extends to much higher thrust levels.

[5]The accelerator electrode actually has a negative voltage to repel the negatively charged electrons in the exhaust beam. If this were not done, the electrons in the exhaust would rush back into the thruster and cause a "short circuit."

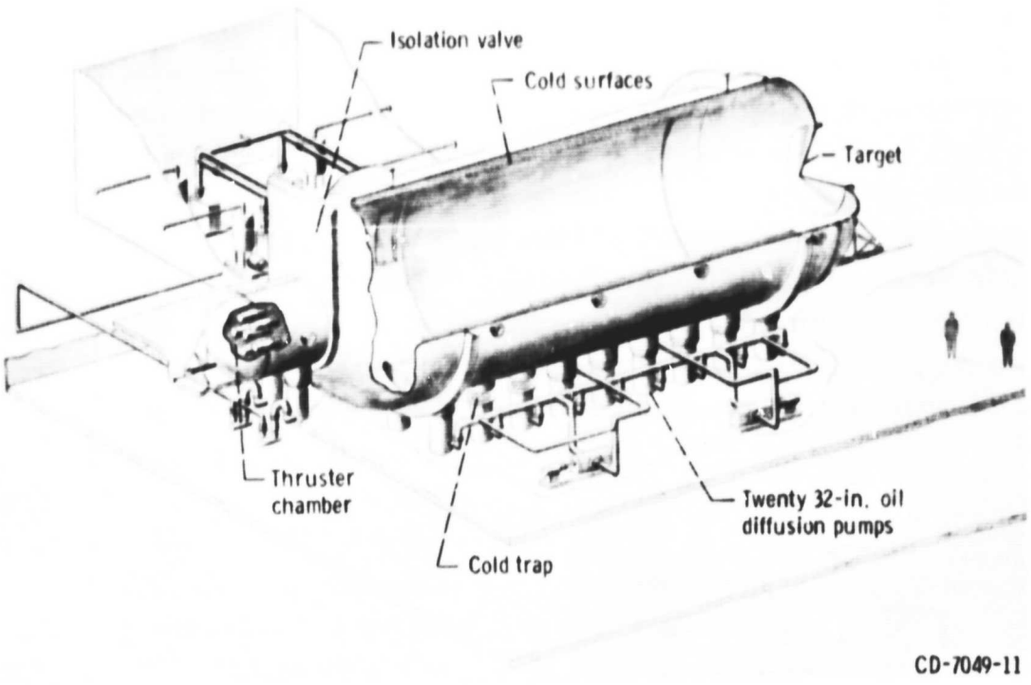


Figure 23.

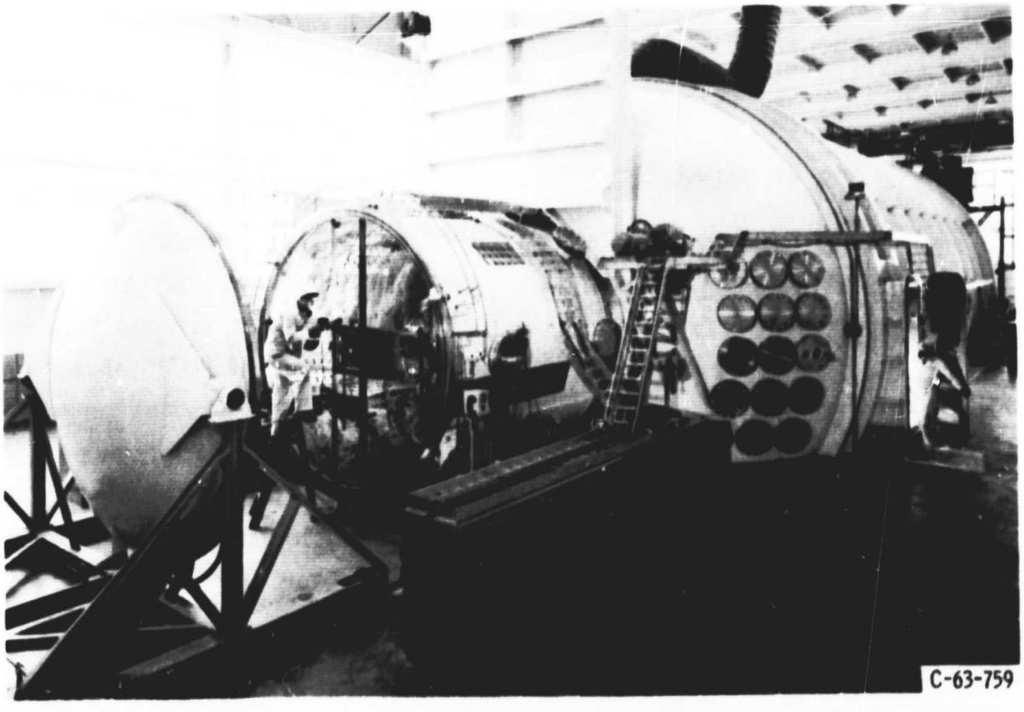


Figure 24.

The three electrostatic thrusters described are high-voltage, low-current thrusters, as contrasted with the plasma thruster. Thus, more power conditioning equipment may be required. However, electrostatic thrusters operate at a higher efficiency than the plasma thrusters, in general, and in this respect compensate for the additional equipment.

Electric thrusters produce small amounts of thrust, and the exhaust products consist mostly of electrically charged particles. Therefore, laboratory testing of thrusters must be done in a vacuum facility. Otherwise, the background air in the laboratory would seriously interfere with thruster operation. Facilities such as the one shown in figures 23 and 24 are thus required for laboratory testing. Typically, these facilities are capable of simulating altitudes of more than 200 miles where the background air pressure is less than 1/100 000 000 of sea-level pressure.

ELECTRIC POWER GENERATION

All the thrusters described in the previous section have one thing in common - they all require electric power. At home, when you need electricity, you simply insert a plug into a wall socket. Unfortunately, in space flight, the problem of obtaining electric power is much more complex. Electrical powerplants of the type that provide the electricity in our homes and factories are far too heavy for space application. Even if they were lightweight, the fuel that they use is a problem. Coal or fuel oil, for example, would be consumed too fast to be carried on a spacecraft. And there are no waterfalls available in space to obtain hydroelectric power. Therefore, engineers have had to find other means of generating electric power in space. Batteries are useful for some short-time applications, but they require recharging, which again requires another power source.

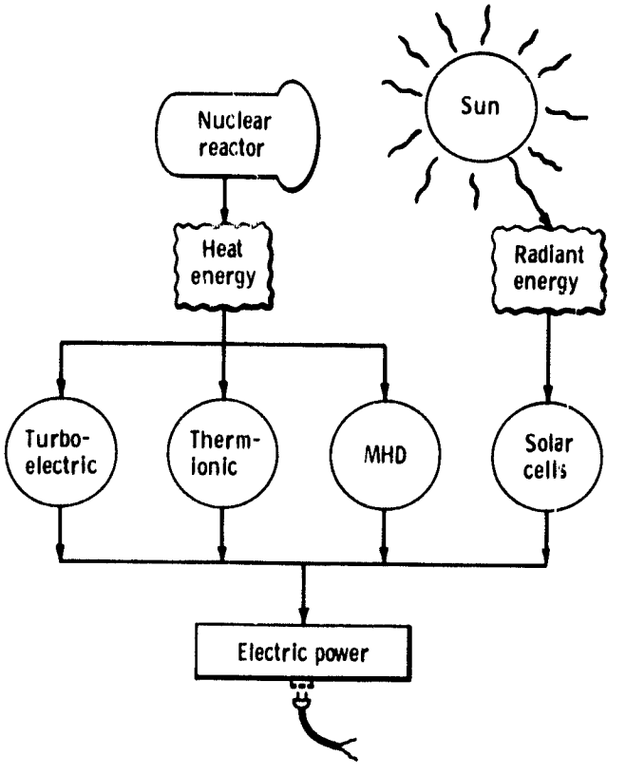


Figure 25.

Nuclear reactors and the Sun are

the two basic sources of energy that might be used for electric propulsion. Because neither of these sources provides electricity directly, an additional component is required to convert the energy they provide into electric power. This energy conversion scheme is illustrated in figure 25. A nuclear reactor provides heat energy. The Sun provides radiant energy. Actually, radiant energy and heat energy are the same form of energy, but they are shown separately in figure 25 because of the different manner in which the energy is used by the components shown within the circles. The units inside the circles represent four different methods of converting energy from the power source into electric power. There are other methods, but the ones shown are presently of greatest interest for electric propulsion. Each of these "power conversion" schemes has certain advantages and disadvantages. These aspects are pointed out in the following sections where the various concepts are described. All the methods to be discussed have been shown to produce electricity, but it is not yet known whether any of these concepts can be made sufficiently lightweight, durable, and efficient for long space missions.

One important measure of performance of the electric propulsion system powerplant is its specific mass:

$$\text{Specific mass} = \frac{\text{Mass of system}}{\text{Electric power produced}}$$

A low-mass system that produces a great deal of electric power is needed. For most electric propulsion missions, a useful powerplant should have a specific mass of less than about 50 grams per watt. Another way of stating this requirement is to say that the powerplant for a thruster that requires 1.0 kilowatt of power (1 kilowatt = 1000 watts) should have a mass no greater than 50 kilograms (1 kilogram = 1000 grams); that is, it should weigh no more than about 110 pounds. By way of contrast, for every kilowatt of power produced by a ground-based powerplant, thousands of pounds of machinery are required. (Even the ground-based powerplants that use nuclear reactors instead of coal or other fuels to obtain heat require this much machinery.)

Nuclear-Turboelectric System

Electric power onboard a spacecraft might be generated by a nuclear-fission - turboelectric system. Heat energy is released in the nuclear reactor when atoms of the nuclear fuel break apart. This breaking apart is called fission. Only certain

kinds of atoms under the right conditions will undergo fission. The nucleus of the uranium-235 atom is very large (many protons and neutrons) and is just on the verge of breaking apart. If an additional neutron enters the nucleus, it can no longer contain all its parts. The nucleus breaks, and two neutrons escape. When this fission occurs, a tremendous amount of energy is released. Part of this energy had been holding the nucleus together. When sufficient uranium atoms are put together in the reactor, enough neutrons enter different uranium nuclei that a continuous fissioning results. The released energy turns into heat, and the fission reactor becomes very hot. A fluid passing through the reactor will absorb the reactor heat and carry it to a heat exchanger (fig. 26). When a spacecraft is manned, a neutron shield must be used to protect the crew from the harmful neutrons escaping the reactor. The heat-transfer fluid will be made radioactive as it passes through the reactor; for this reason, a shield against gamma rays is also required. In a two-fluid system, heat is transferred from the reactor coolant fluid to the working fluid. The working fluid is not made radioactive by the gamma radiation and, therefore, need not be shielded after it passes through the gamma shield. The working fluid is heated to such a high temperature that it turns into vapor. This vapor is at a high pressure, and as it passes through the turbine (fig. 27) blows on the turbine blades and spins the turbine on its shaft, much as moving air spins a windmill.

Vapor being exhausted from the turbine must be cooled and condensed before it flows back to the heat exchanger, where it is heated and vaporized again. Because space is a vacuum, cooling can be accomplished only by radiating the excess heat. A large radiator (fig. 27) is required. The size of this radiator can be reduced if the temperature is made as high as possible. The amount of heat radiated from a given surface increases very rapidly as the surface temperature increases. Because of this fact, the reactor coolant and heat-transfer fluid used in most space

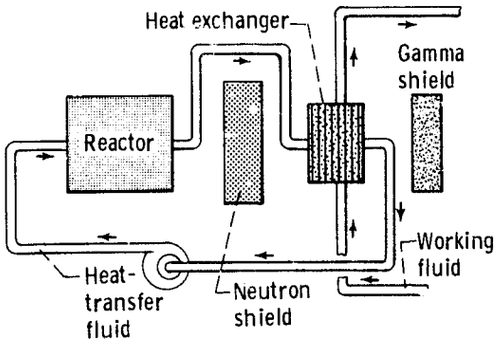


Figure 26.

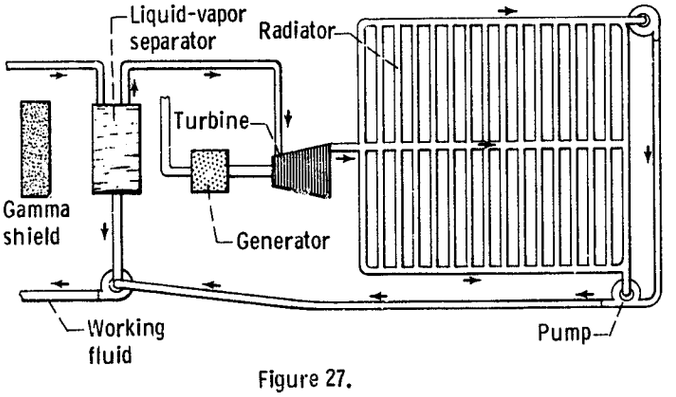


Figure 27.

nuclear power schemes is a liquid metal, such as potassium or lithium. These metals liquefy and vaporize at very high temperatures.

The radiator also must have tube walls that are thick enough to prevent micrometeoroid punctures which would allow the working fluid to leak out. Thick tube walls, however, increase radiator weight. This weight problem can be alleviated somewhat by clever designs, such as the use of many closed chambers containing vapor, rather than solid fins or continuous tubing, to conduct the heat over the large area needed. Puncture of several of these chambers by micrometeoroids can be tolerated because only a small amount of vapor is lost with each puncture. The chamber walls can, therefore, be quite thin, and thus the weight is reduced.

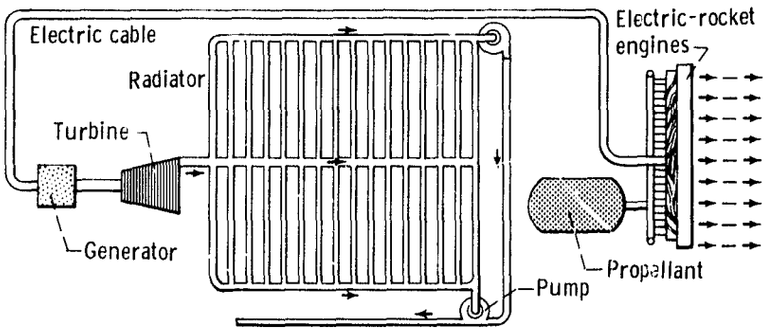


Figure 28.

Finally, the spinning turbine shaft drives the electric generator, which produces the electricity used to run the electric thrusters (fig. 28). All the basic theory is understood, so that, in principle, a system of this type could be built today. However, finding suitable materials and component designs to operate reliably for long periods of time at the required high temperatures still requires much research and development. The nuclear-turboelectric system, like the nuclear-thermionic and nuclear-MHD systems discussed in the next sections, is attractive where several million watts of power would be required, such as, for example, during manned expeditions to Mars.

Nuclear-Thermionic System

If the primary source of power is heat, the thermionic converter is, in one major respect, ideal. It provides a means of converting heat directly to electricity without any moving parts or heavy fluids. Such conversion is possible because a piece of metal, when heated, emits (or boils off) electrons. This thermionic effect was first discovered by Thomas Edison about 1880. It was not until the early 1960's, however, that serious consideration was given to using the thermionic effect to con-

vert heat to electricity. This elapse of many years was caused by the serious practical difficulties involved in this kind of conversion, which are discussed in the succeeding paragraphs. Difficulties associated with making the thermionic converter efficient are still the subject of research.

The thermionic diode has two electrodes, as depicted in figure 29. One electrode (the cathode, or emitter) is heated and emits electrons, while the other electrode (the anode, or collector) is cooled and collects electrons. If the two electrodes are electrically connected through an electrical load (e.g., a motor), electric current can flow and work can be done. This has been demonstrated in the laboratory. But, if an enormous amount of heat energy (a large, heavy, nuclear reactor) is needed just to produce a small amount of electric energy, the thermionic converter is not practical. Hence, scientists must investigate just how the thermionic converter can be made more efficient, that is, how more electric energy can be obtained for the same amount of heat energy. If everything else remains the same, the hotter the emitter is, the larger the current is. Of course, this process is limited as the weakening or melting point of the emitter is approached.

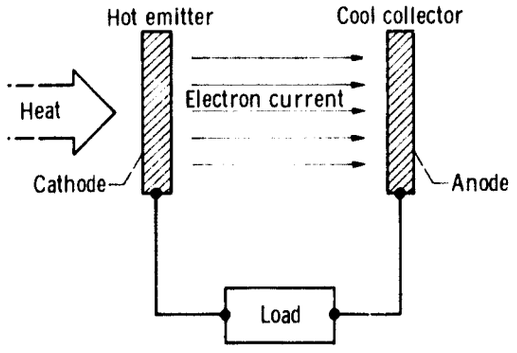


Figure 29.

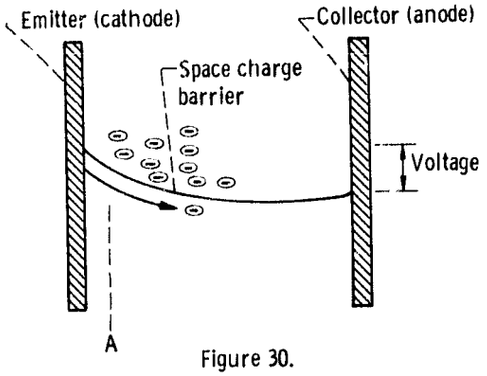


Figure 30.

A vacuum thermionic diode is one that is enclosed within a container from which all air (and other gases) has been removed. In figure 30, a typical potential diagram for a vacuum thermionic diode is shown with the electrodes spaced far apart. A voltage results from the electron flow from the hot emitter to the cool collector. The electric potential looks, to an electron, as if a large negative charge barrier were present between the two electrodes. The flowing electrons cause just this sort of negative charge to exist, with the electrons between the plates tending to repel newly emitted electrons. With this situation existing, it is easy to see that only those electrons that are emitted with enough energy to pass through the potential barrier can reach the collector.

This negative charge in the interelectrode space caused by the electron flow it-

self is called the space charge. Unfortunately, the space-charge barrier in a wide-spaced vacuum diode is so large that the current to the collector is very small. One solution to this problem is to move the collector so close to the emitter that it is far inside the space-charge barrier, such as at position A in figure 30. Useful power output, obtained by this approach, would require electrode spacings of 0.0001 inch or smaller. This requirement not only poses great difficulties in fabrication but also severely curtails the useful life of the diode.

The next question is, then, is there any way the space-charge barrier in figure 30 might be reduced without bringing the electrodes so close together. The answer lies in devising some way of introducing a positive charge (ions) to "neutralize" the effect of the negative space charge (electrons). This approach has resulted in the "gaseous thermionic diode." The most highly developed gaseous diode is the cesium diode. In this diode, cesium vapor is introduced and on contact with the hot emitter (usually tungsten) becomes ionized (as in the "contact-ionization" ion thruster). The cesium ions then flow in the interelectrode space, neutralizing a portion, or all, of the space-charge barrier. This situation is not achieved without the appearance of other problems, however, so that other types of gaseous diodes that employ other gases and other means of ionization are currently being studied. The objectives of these other studies, though, remain the same. One of the major developmental problems of thermionic diodes is lifetime. High operating temperatures improve efficiency but decrease the lifetime of the diode. Materials better able to withstand the high temperatures and corrosive action of such gases as cesium are required.

The output voltage of a single thermionic diode is about 1 volt. Diodes must be connected in series to obtain higher voltages. Output current densities are about 10 amperes per square centimeter in gaseous thermionic diodes. Thus a single diode with an area of 3 square centimeters (about 0.5 sq in.) can produce 30 watts of electric power. A thruster that required 3 kilowatts of power would need 100 diodes of this size.

To produce a nuclear thermionic power system would require that many thermionic diodes be adjoined to the nuclear fuel elements in a nuclear reactor, so that the heat generated by the fissioning uranium would be applied directly to the electron emitter electrodes (cathodes). A liquid-metal coolant would flow through the reactor to cool the collector electrodes (anodes), so that electric power is generated. If the anodes were not cooler than the cathodes, they would also emit electrons and no net current would flow. The coolant would carry the excess heat out of the reactor to a radiator. The nuclear-thermionic system might therefore look something like fig-

ures 26 and 27, except that the turbine and the generator would be eliminated, and a much more compact system could be achieved.

Nuclear-Magnetohydrodynamic System

An alternative to the use of the turboelectric generator or thermionic diode concepts in the nuclear-fission power system is the magnetohydrodynamic (MHD) generator (fig. 31). This device works on the principle that when a conductor is moved through a magnetic field, an electric field is induced in the conductor perpendicular to both the direction of motion and the magnetic field. This induced electric field causes an electric current to flow through the conductor in the electric-field direction. In the MHD generator, the moving electric conductor is usually a hot, flowing, ionized gas which is forced through a channel across which a magnetic field is applied. Some research is also being done using flowing liquids instead of gases. Electric power is extracted from the device by conducting the electric current out of the generator through electrodes placed on the side walls.

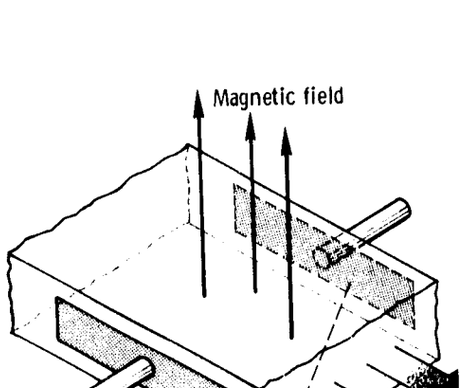


Figure 31.

The principle of operation of the MHD generator is related to the previously described electromagnetic (plasma) thruster (fig. 14). In the plasma thruster, an electric current is forced through a gas, producing a plasma (ionized gas). The interaction of the current with a magnetic field then causes a force to be exerted on the plasma. This force accelerates the plasma in proportion to the electric power input to the thruster. In the MHD generator, a hot gas is forced to flow through a magnetic field and an electric current is produced. The interaction of the current with the magnetic field produces a force opposite to the gas flow direction and thus slows the flow. Some of the energy given up in this process is converted into electric power output of the generator (fig. 31).

The greatest advantage of the MHD generator is that it generates electric power

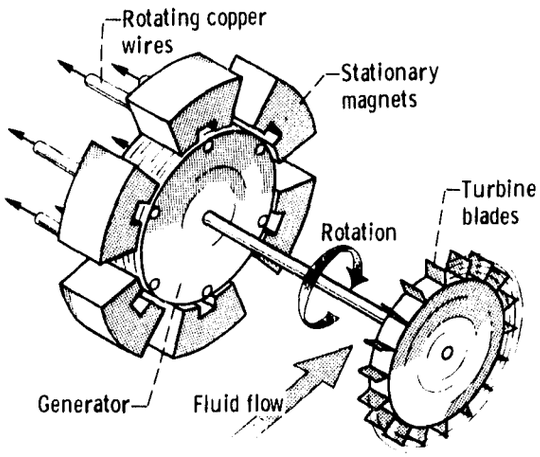


Figure 32.

directly from the working fluid. In contrast, the turboelectric generator (fig. 32) first converts fluid flow energy into mechanical rotational energy in a turbine, which then rotates a generator rotor. Electric energy is induced in the copper wires of the rotor as they pass through the magnetic field of stationary magnets. Because the MHD generator requires no rotating parts, its great advantage is that it can operate at much higher temperatures. This higher operating temperature can be utilized to obtain higher conversion efficiencies and thereby reduces the system radiator size. This reduces the weight of the system at a given power level.

Before MHD generator systems complete with nuclear-reactor heat sources can be built and tested, answers to many important design questions must be obtained. Researchers have conducted simulation tests to obtain some of these answers. For example, the hot exhaust from a rocket engine has been used as a conducting fluid. Tens of megawatts of power have been produced for brief intervals of time in this manner. These tests have demonstrated the feasibility of MHD generators.

In the MHD generator, as in all generators, the electric current is carried by moving electrons. Therefore, the electron concentration and the ability of the fluid to conduct electrons is important to efficient operation. The higher the concentration of electrons and the better the fluid conducts them, the higher will be the power output of the generator. The ability of the fluid to conduct electrons depends on the type of fluid and its temperature. The electron concentration increases rapidly with temperature. In the previously mentioned MHD experiments, the combustion gases were "seeded" with small percentages of alkali metal vapor, such as cesium or potassium. This vapor was readily ionized at the temperature of the combustion gases (~3000 degrees kelvin) to produce sufficient electrons to conduct the current. It does so down to temperatures of about 2000 degrees kelvin. Below this temperature, its electron concentration is too small for effective generator operation.

For space power applications, combustion power sources are not feasible because of their high rate of fuel consumption. Using the combustion products directly in a chemical rocket would be much more efficient. Hence, high-temperature

nuclear-fission reactors must be used to heat the fluid. However, even the most advanced reactors now being contemplated do not operate at gas temperatures sufficient for the temperature alone to produce an electron concentration of the magnitude required for efficient operation of an MHD generator. For space power applications, the generator must operate on another principle for producing electrons to carry the electric current.

This "nonequilibrium" principle is based on the fact that not all the energy converted from the flowing gas can be extracted from the generator. That portion of the energy which is not extracted is returned to the electrons in the form of heat, which tends to raise their temperature above that of the gas. In gases such as argon and neon, this electron temperature can, under certain conditions of operation, be many times that of the gas. The electron concentration is determined by the electron temperature rather than the gas temperature. It is, therefore, possible to obtain a much higher electron concentration and a greater conductivity in certain gases than one would expect from the gas temperature alone. This result is known as the nonequilibrium conductivity effect.

Several experiments intended to demonstrate the feasibility of nonequilibrium MHD generators are in various stages of construction and testing. At the NASA Lewis Research Center, for example, a closed-loop facility (fig. 33) is being tested. "Closed-loop" means that the same gas is used over and over again, as would be required in space. This experiment uses argon seeded with cesium vapor as the gas, which is heated by a graphite heater to simulate a nuclear reactor operating at approximately 2000 degrees kelvin. Experiments, such as the one shown in figure 33, are providing much of the necessary information needed to determine whether lightweight MHD systems for space power can be built.

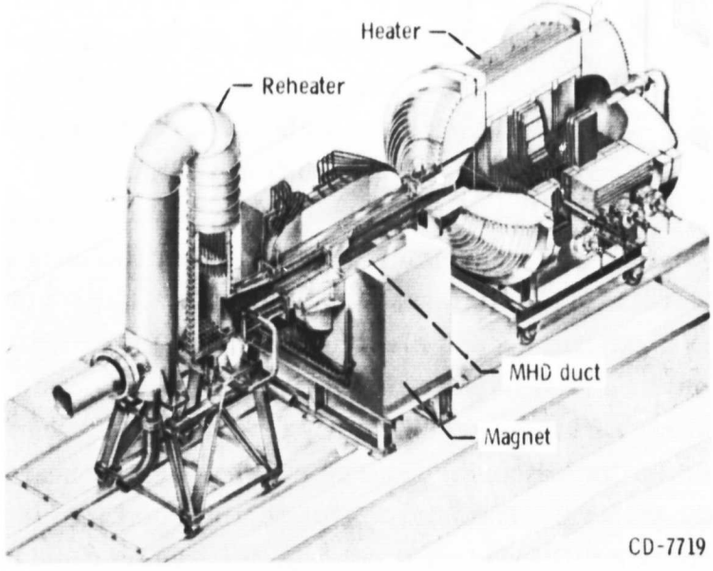


Figure 33.

Solar-Cell System

In a solar cell, radiant energy from the Sun is converted directly into electric energy by photovoltaic action. Sunlight is a "free" energy source - it is the fuel for the system. Solar cells made from silicon crystals, sliced into thin wafers, have been used as the main power source in most unmanned satellites and in all lunar and planetary missions. They can, therefore, be regarded as an available source of space power, in contrast to the nuclear systems, which are still mostly in research and development stages. The existing solar-cell systems, however, are too heavy (too high a specific mass) for major electric propulsion applications. Research and development is continuing in order to reduce this weight. The attainable reductions make solar cells very attractive for many missions that require rather low amounts of power. But, for the range of hundreds of kilowatts or megawatts, solar cell arrays are both too bulky and too heavy.

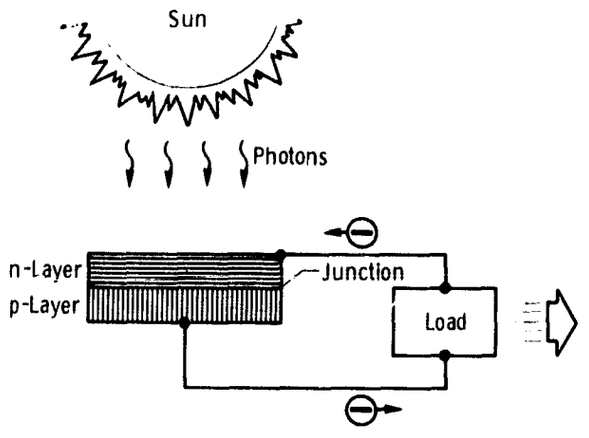


Figure 34.

Solar cells are made of thin wafers of a semiconducting material that contains specially added impurities. An "n-on-p" silicon solar cell is illustrated in figure 34. In this concept, the n-layer (negative layer) has an excess of electrons that are free to move about (donors), and the p-layer (positive layer) has a shortage of these electrons. Solar radiation striking the n-layer excites some of the donor electrons causing them to move to the p-layer. This movement results in a difference in charge, or voltage, between the two layers. The voltage built up in this way provides the "electric pressure" necessary to make the excess electrons in the p-layer flow through wires and external circuits on their way back to the n-layer. This electric power can be used to operate the electric thruster, which is represented as a "load" in figure 34. The impurities required in the silicon are introduced by passing heated phosphorus gas over the surface of the wafers. The phosphorus is absorbed into the silicon (in the amount of 10 to 20 parts per million) to a depth which is determined by the length of the heat-treating time. The line separating the phosphorus-treated part of the wafer (the n-layer) from the pure silicon portion (the p-layer) is called the junction.

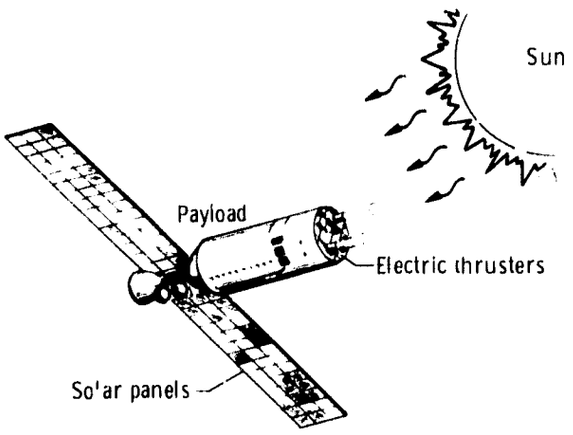


Figure 35.

Because they have no moving parts, and because they use an energy source that is free (the Sun), solar-cell, power conversion systems are very attractive for low-power, electric propulsion missions. (A solar-electric rocket is illustrated in fig. 35.) Solar-cell systems, however, have limitations that make investigators continue to seek ways of improving their performance and also to research other more advanced systems. For example, operation at maximum efficiency requires that the cells always be pointed at the Sun. This complicates spacecraft design in that some methods of controlling the orientation of the solar panels must be incorporated. Another problem is associated with the size of the silicon wafers. Typical silicon cells have less than 0.5 square inch of surface that is exposed to the Sun. Each cell converts about 10 percent of the sunlight that strikes it into usable electricity. Therefore, obtaining thousands of watts of electric power would require several hundred square feet of solar cells. Because each cell provides about 0.025 watt of low-voltage power, an area of solar cells about the size of a baseball diamond would be required to obtain 60 000 watts and it would contain more than 2 million solar cells. This large area of solar cells creates a problem for the spacecraft designer who must determine how to package them so that they can be launched through the Earth's atmosphere and then deployed in space. Finally, the intensity of the Sun's radiation decreases with distance from the Sun. Thus, the available power of an interplanetary spacecraft will decrease as it moves away from the Sun. The spacecraft must be designed to account for this loss.

To overcome some of these problems, scientists are investigating new kinds of solar cells. One promising cell under development in the laboratory is made from cadmium sulfide and cupric sulfide layers that are vapor deposited onto a thin plastic film. Vapor deposition is the condensation of a gas on a cold surface, similar to the

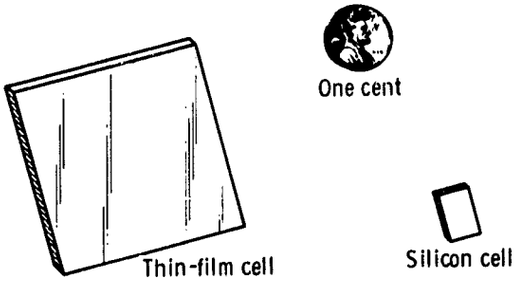
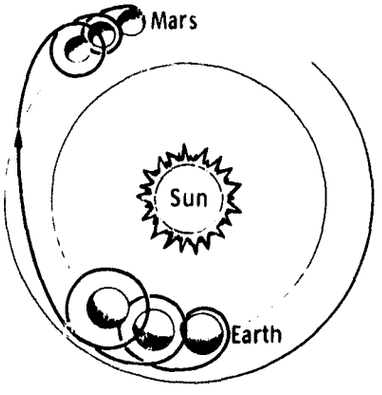


Figure 36.

way frost forms on a window when someone breathes on it. Although it has not yet been perfected, the new cell is lightweight and flexible. It can be rolled and unrolled without damage. Individual cells have more than twice the area exposed to the Sun than a silicon cell (see fig. 36) but thin-film cells are only about one-half as efficient. Therefore, although fewer cells are required to provide the same amount of electric power, their surface area is greater.

ELECTRIC PROPULSION MISSIONS

We have seen in the previous section that a wide variety of thrusters and power generation systems is possible. It is not at all clear yet just which thruster together with which power generation system will prove to be best for the various applications of electric propulsion. Of the power generation systems described, only the solar-cell systems have been actually used in space applications. Of the thrusters described, the electrothermal thruster is attractive for certain applications because it is the simplest, but its exhaust velocity is limited. Therefore, it might require more propellant than the plasma or ion thrusters for the same mission. The plasma thruster is basically a low-voltage, high-current device, which makes it attractive for direct coupling to some of the power generation concepts that have similar characteristics. Because it is not yet well understood, much more work must be done on the plasma thruster to improve its performance. The ion thrusters are fairly well advanced, and, although they require high voltages to operate efficiently, engineers believe they know how to design and build useful ion thruster systems for some applications. The wide range of possible applications for electric propulsion makes it seem likely that there will be a need for a number of different systems. Figure 37 shows the approximate power levels required to perform a number of different missions. It is evident from the figure that the more difficult missions require large amounts of



Applications	Kilowatts of power
Attitude control	0.01 to 0.10
Station keeping	0.01 to 1.0
Satellite raising	1.0 to 10
Lunar ferry	10 to 1000
Interplanetary probes	1.0 to >1000
Manned interplanetary flights	>1000

Figure 37

electric power, which, as we have seen, must also be provided by a very lightweight system.

SERT I

On July 20, 1964, two ion thrusters were tested in space by NASA. One was a mercury electron-bombardment thruster, developed by the NASA Lewis Research Center, the other was a cesium contact-ionization thruster developed by the Hughes Research Laboratories under NASA contract. This test was known as the SERT I (Space Electric Rocket Test I). The battery-powered thrusters were mounted on a capsule that was launched with a Scout solid-propellant rocket into a ballistic trajectory (see fig. 38). The primary purpose of SERT I was to test the performance of

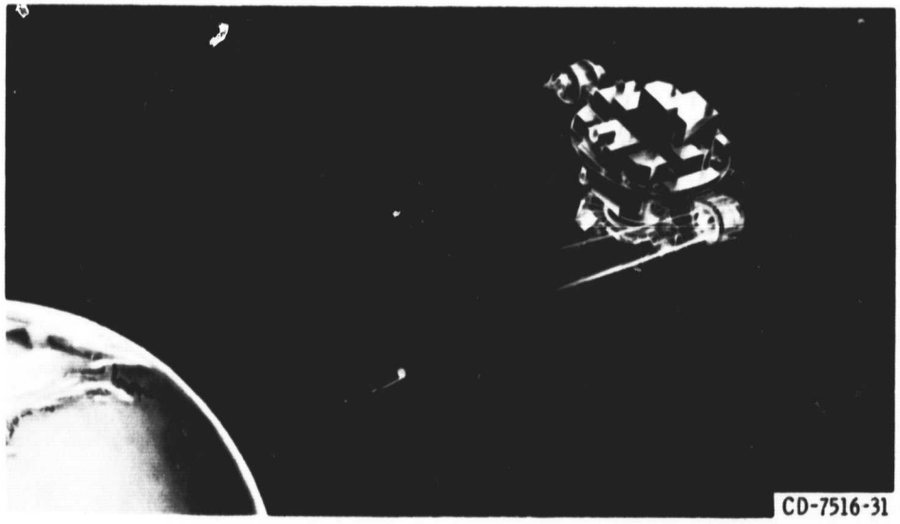


Figure 38.

the ion thruster in space. These thrusters were operated on the ground for hundreds of hours in vacuum tanks, which simulate the environment of space. The thrusters operated quite well in vacuum tanks, but the exact environment of space cannot be fully simulated in any tank in which thrusters are operated. For example, the cesium or mercury ions from the thrusters strike the walls of the vacuum tank and may knock many electrons loose from the walls (fig. 39). These electrons may enter the exhaust beam and neutralize the ion space charge described previously. When this neutralization occurs, it is difficult to tell if the electrons from the thruster

neutralizer are doing their job of neutralizing the ion beam.

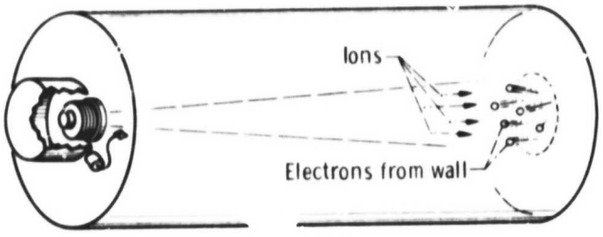


Figure 39.

Because electric rocket thrusters have only a small thrust, the 50-minute SERT I ballistic flight would not have been long enough for the thruster to push the spacecraft one way or the other. Therefore, the thrusters were mounted on arms so that their thrust would spin the toplike spacecraft. The mercury electron-bombardment thruster onboard SERT I operated, as predicted from vacuum chamber tests, and produced thrust. Thus, the very important principle of neutralization was proved.

The cesium thruster onboard SERT I did not operate, but on August 29, 1964, a cesium thruster produced thrust in a similar space test by the U.S. Air Force. The Air Force test thruster was developed by Electro-Optical Systems, Pasadena, California. Small electrothermal resistojet thrusters have also been successfully tested in space since 1964 and have been used on several space missions. Small plasma thrusters have also been tested in space. Thus, it has been established that electric thrusters will work in space and that their performance in space can be predicted from groundbased tests in vacuum facilities. The next step is to determine how durable the thrusters are. We saw earlier that because electric thrusters produce only a small amount of thrust, they must be capable of operating for long periods - up to several months, in some applications.

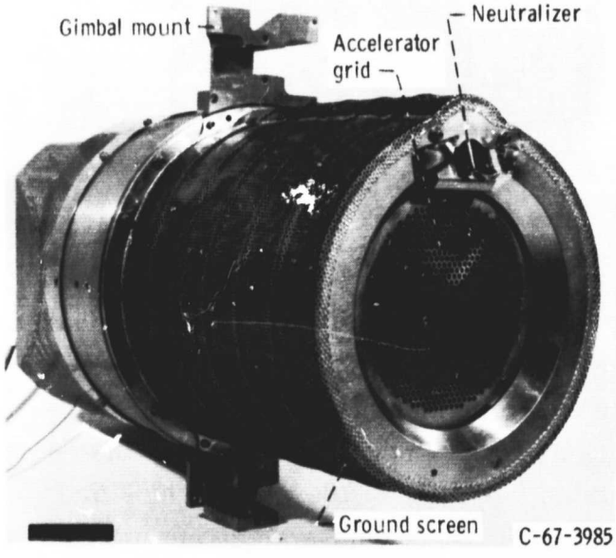


Figure 40.

SERT II

To determine the durability of ion thrusters in space, NASA is conducting the SERT II program. The purpose of this program is to operate a 1-kilowatt mercury electron-bombardment thruster in space for up to 6 months. Figure 40 is a photograph of the thruster, which generates an ion beam about 6 inches (15 cm) in

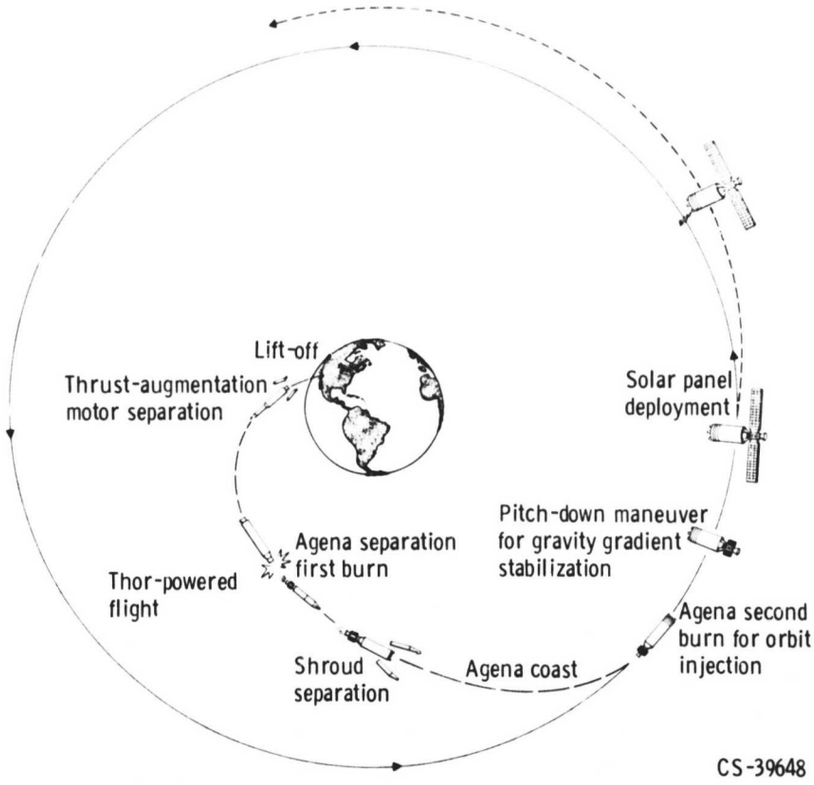


Figure 41.

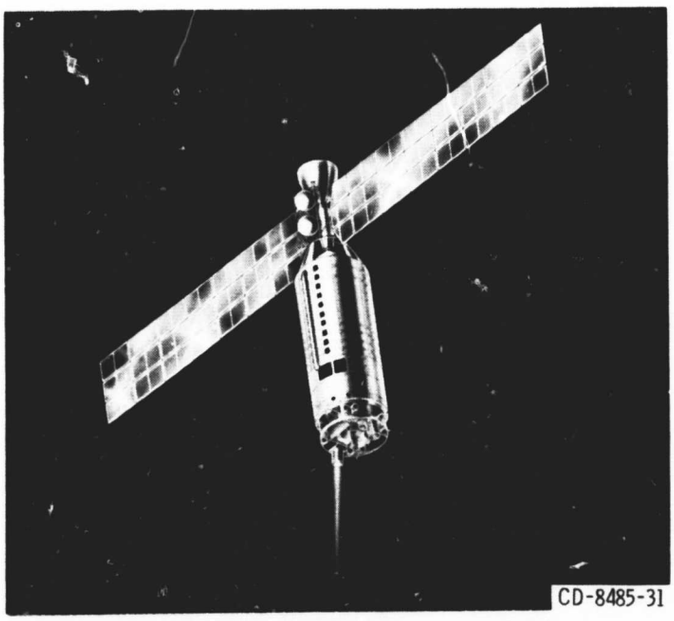


Figure 42.

diameter and produces about 0.006 pound thrust. A Thorad-Agena booster will be used to launch it into a circular polar orbit, as shown in figure 41. The polar orbit permits the solar-cell panels, which provide the necessary electric power, to remain in continuous sunlight throughout the mission duration. The solar-cell panels (fig. 42) each measure 1.5 by 5.8 meters.

There are two thrusters on the spacecraft shown in figure 42, each with its own power

conditioning subsystem. Only one thruster will be used. The second is a "standby" if there is difficulty with the first system. The exhaust from the thruster will be directed mostly toward the Earth. The orbital altitude will change only slightly during the test. Depending on the launch date, after a maximum of 6 months, the spacecraft orbit will pass into the Earth's shadow at times. During these periods no electric power will be available to operate the thruster.

Tests such as the SERT II will provide mission planners with the important data needed to design primary propulsion systems for long-duration missions. Other tests have been undertaken or are presently underway to evaluate the potentialities and durability of smaller electric thruster systems for use for auxiliary propulsion.

Auxiliary Propulsion

The first application of electric propulsion systems has been for control of Earth-orbiting satellites. In this application, these propulsion systems are considered as auxiliary systems. Weather and communications satellites must be held in specific orientation with respect to the Earth so that their cameras, instruments, and antennas may do their jobs properly. The function of controlling satellite orientation is known as attitude control (see fig. 43). Also, some satellites, for example, synchronous satellites, must be held in position over one fixed spot on Earth. These satellites revolve around the center of the Earth once every 24 hours, the same length of time that it takes the Earth to revolve once. Thus, the satellite position remains fixed in relation to the Earth. Because of gravitational influences of the Sun, Moon, and other celestial bodies, small disturbance forces acting over long periods of time tend to cause the satellite to drift off position. The function of counteracting these forces and keeping the satellite at the proper location is called station keeping

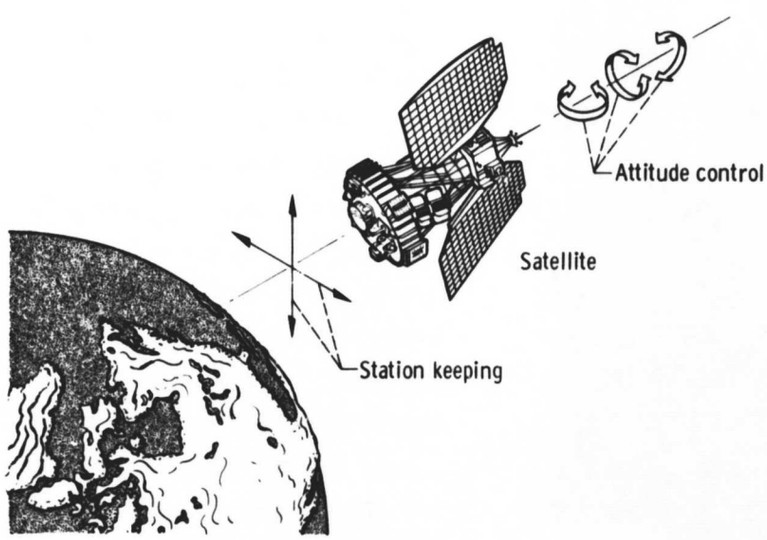


Figure 43.

(see fig. 43). Auxiliary electric propulsion systems that perform attitude-control or station-keeping functions do so by producing micropound levels of thrust.

Resistojet thrusters have been used since 1965 to perform certain short-duration station-keeping functions. They show great promise for additional applications where propellant storage capacity is not limited. Because of their higher propellant exhaust velocity, reduced propellant tankage requirements, and "thrust vectoring" capability, ion thrusters are also well suited for these applications. Thrust vectoring is the ability to alter the direction of the exhaust beam and, hence, the direction of the thrust. Ion thrusters can perform this function easily because the exhaust beam consists of charged particles and their direction of motion can be affected by electrical means, as illustrated in figure 44. The top section of the figure shows the unvectored beam. The accelerator electrode sections are both at the same potential. The lower section shows the vectored beam, which results from changing the potential of one segment of the accelerator relative to the other. Note that positively charged ions are attracted toward the more negative electrode segment. Very precise thrust vector control is possible without the use of any moving parts. This capability, incorporated into a thruster, represents a system simplification that also reduces the number of thrusters that might be needed on a satellite. The contact-ionization thruster has already demonstrated this feature. Flight tests of bombardment and colloid-particle thrusters for auxiliary propulsion may be performed in the future.

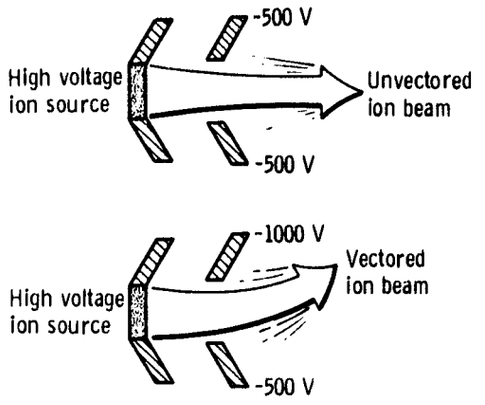


Figure 44.

Unmanned Primary Propulsion

As electric propulsion technology develops, many promising subsequent applications, after auxiliary propulsion, become evident. These applications, if they are realized in the near future, would probably utilize solar-cell, power generation systems. Even with the inherent limitations of solar-cell systems described earlier, many important missions may be accomplished. Among these are raising satellites to synchronous orbits about Earth, instrumented probes to the distant planets such as Jupiter or Saturn or to certain comets, and probes that depart from the ecliptic

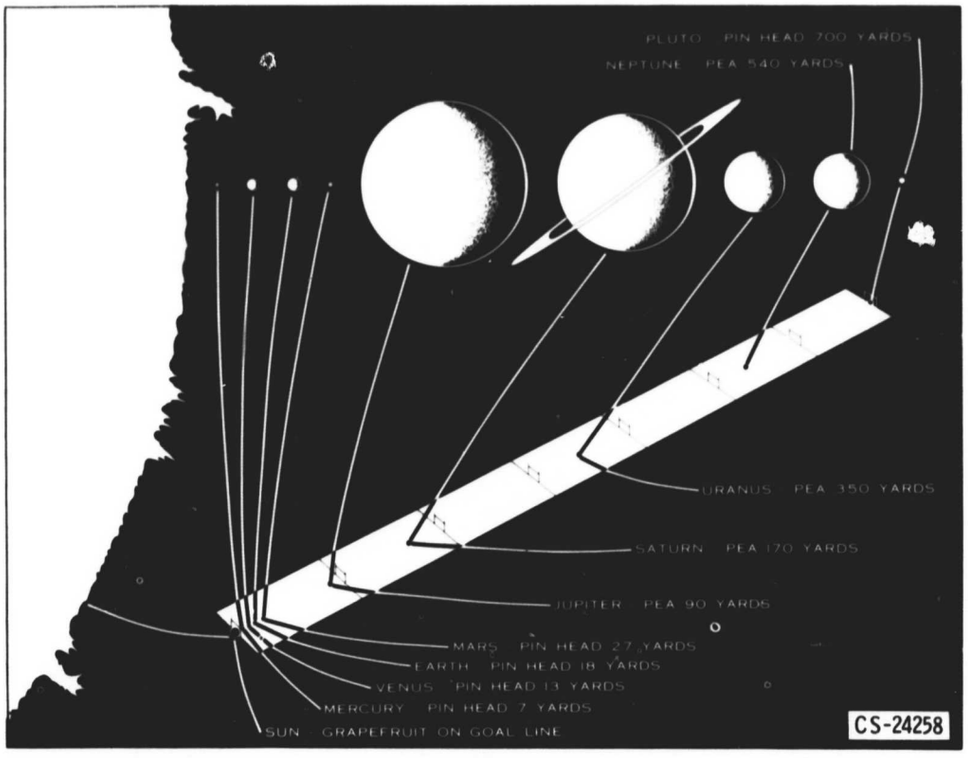


Figure 45.

plane. The ecliptic plane is the plane in which the Earth circles the Sun. All other planets (see fig. 45) rotate in planes that are close to the ecliptic plane. These probes are important to gather scientific information on the universe and also to prepare the way for future manned flights.

Figure 46 shows a model of an unmanned solar-electric spacecraft that might be used for carrying an instrumented scientific package to Jupiter. It was designed at the Jet Propulsion Laboratory, Pasadena, California. The spacecraft is equipped with five electron-bombardment thrusters, one of which is a spare to be used if any of the others fail to operate. Each thruster requires about 2.5 kilowatts of electric power. Because the Sun's energy to the solar cells decreases with increasing distance from the Sun, the thrusters would be cut back in power, one by one, as the distance increased and then would be turned off. The remaining thrusters would then operate at full power and peak efficiency.

One advantage of using electric propulsion for missions of this type is that the application of low thrust over long periods of time permits spacecraft trajectory corrections to be made on an almost continuing basis. In contrast, the high-thrust, chemical-propulsion systems launch the spacecraft with a short burst of thrust

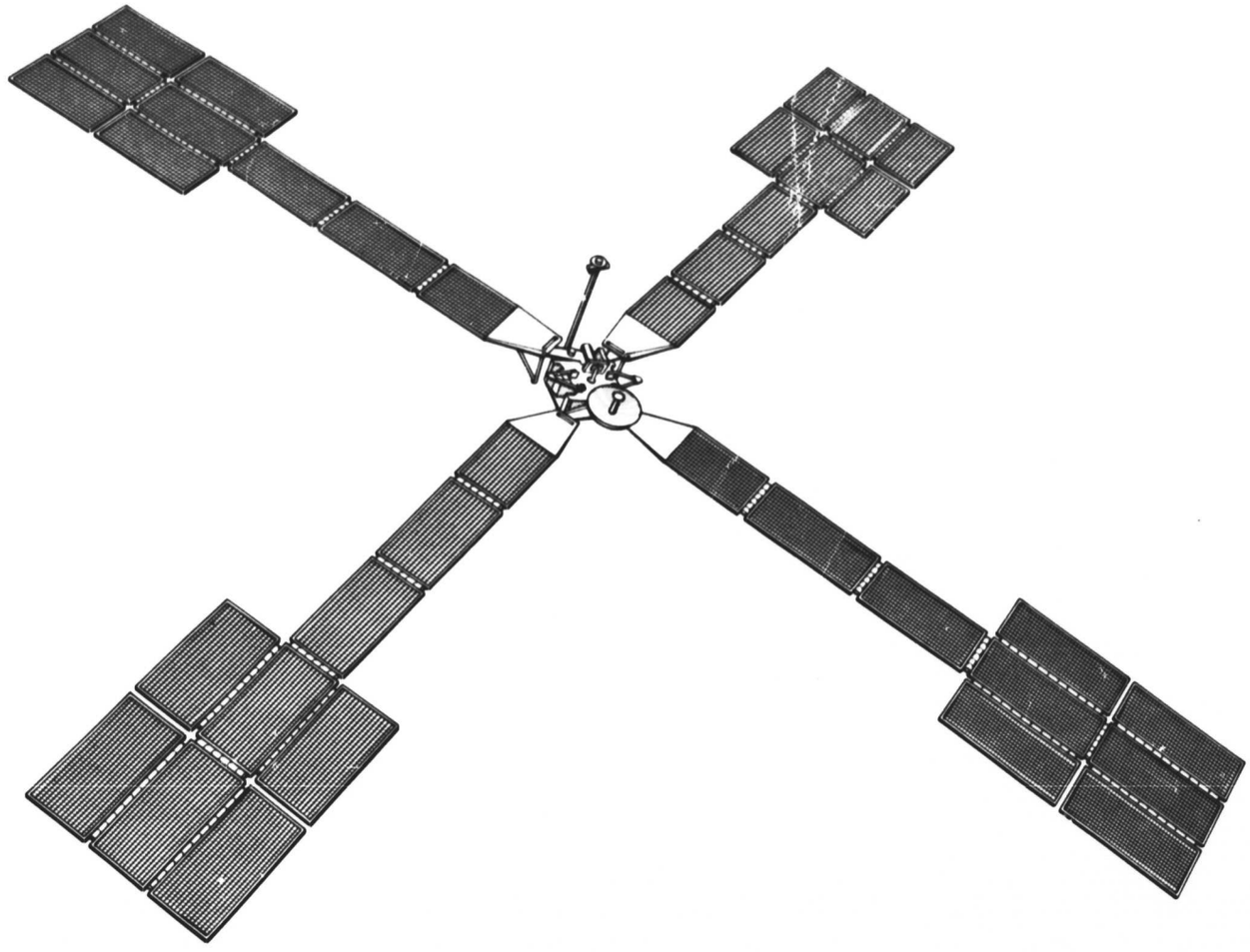


Figure 46.

followed by long coasting times and require high "pointing" accuracy. In addition, once the electrically propelled payload has reached its destination, the power generation system is available as a source of power for the various instruments and experiments onboard.

Manned Primary Propulsion

As shown previously, manned electric propulsion applications require large amounts of electric power, possibly several million watts. Much more research and development on high-power, lightweight, power generation systems and thrusters must be done before manned electrically propelled spacecraft will be available.

Conceptual design studies of what such a spacecraft might be like are made by propulsion system engineers and mission planners to establish practical arrangements, to estimate weights and sizes of components, and to identify major areas requiring further study and experimentation.

An interplanetary electric-powered spacecraft to carry men to Mars and back to Earth might look like that depicted in figure 47. This spacecraft could carry an

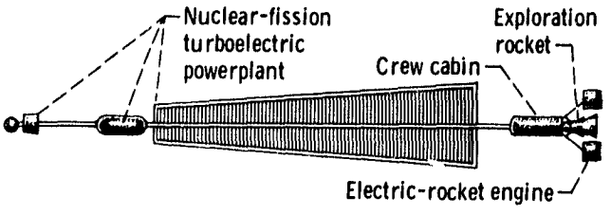


Figure 47.

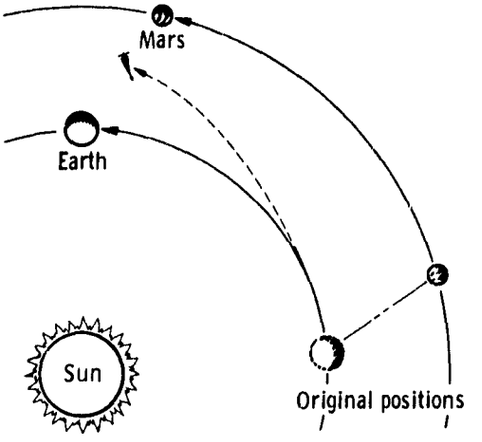


Figure 48.

eight-man crew to Mars and back to Earth. It would be 400 feet long and weigh nearly 1/2 million pounds. The vehicle would be launched using two Saturn V boosters and assembled in orbit before proceeding to Mars. Electric power onboard the spacecraft is provided by a nuclear-turboelectric system. After assembly, the spacecraft proceeds on a flight path for a rendezvous with Mars. When it is about halfway to Mars, the spacecraft will be orbiting the Sun faster than Mars because it is closer to the Sun. To slow the spacecraft to the speed of Mars, it must be swung around (fig. 48) in order to apply the necessary reverse thrust. When the spacecraft reaches the gravitational field of Mars, it must spiral down to a satellite orbit around Mars. It continues to thrust backward as it spirals down.

If the surface of Mars is to be explored, some of the crew must descend from orbit in a chemical exploration rocket (fig. 49). The main spacecraft would orbit Mars until its crew returned in the chemical rocket. Both Earth and Mars are moving during the trip to Mars and the exploration of Mars. When the spacecraft

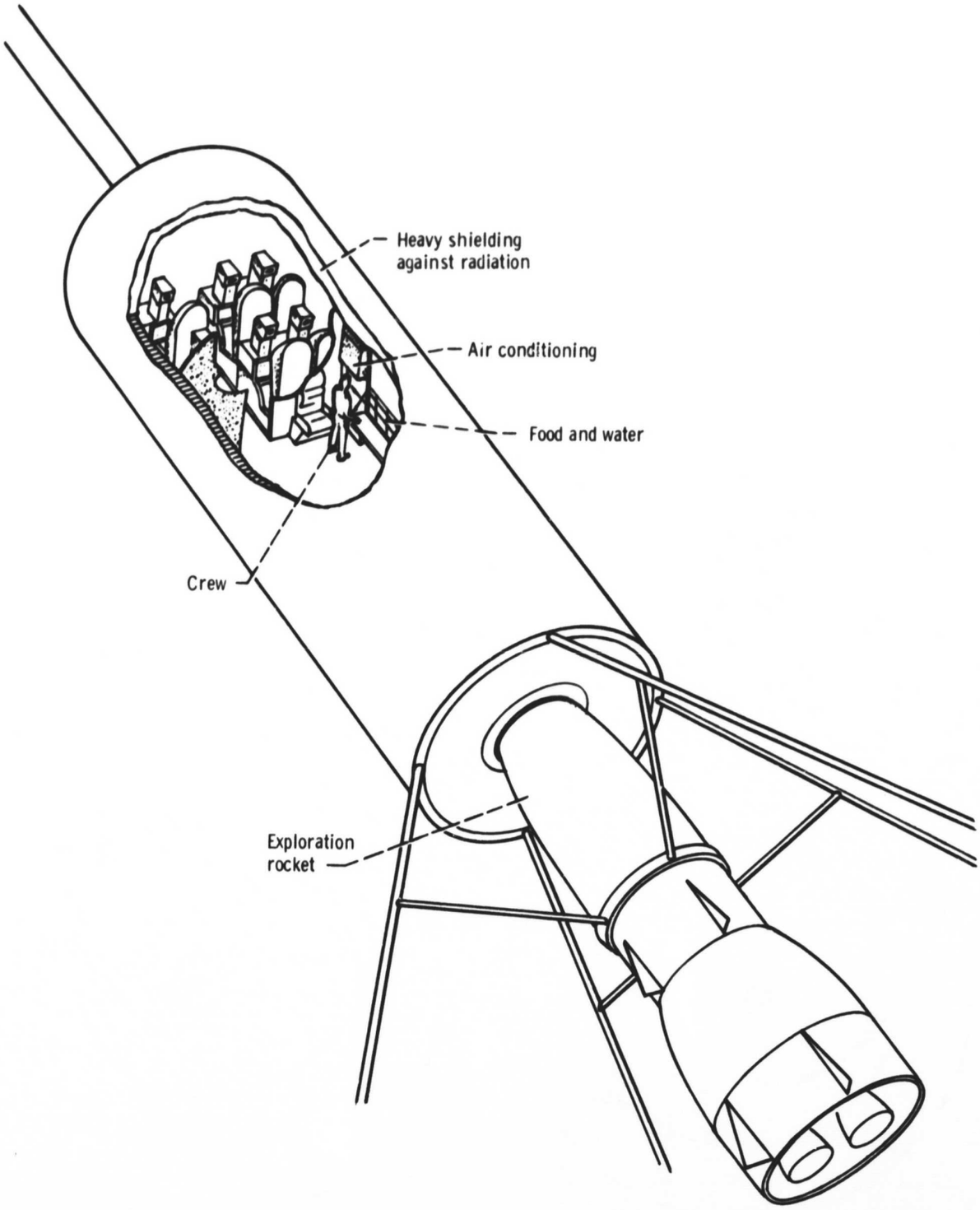

Heavy shielding
against radiation
Air conditioning
Food and water
Crew
Exploration
rocket

Figure 49

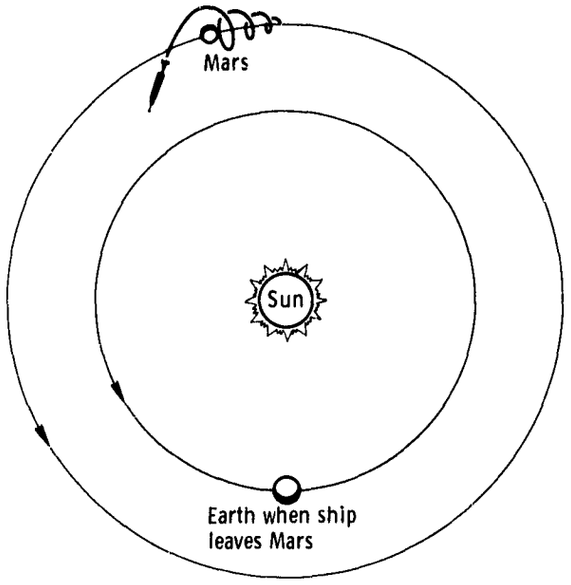


Figure 50.

leaves Mars for the return trip, the two planets will be in the position shown in figure 50. The Earth is orbiting the Sun faster than Mars, and, therefore, the spacecraft must increase its speed to catch the Earth. It takes a shortcut, as illustrated in figure 51. The shortcut passes inside the Earth's orbit, and the spacecraft will then be going too fast to rendezvous with Earth. It must be turned around in order to use the electric rocket engines as brakes (fig. 52). After rendezvous, it will spiral down into an orbit about Earth. Once in Earth orbit, the crew can land in reentry capsules similar to the Mercury or Gemini vehicles. These reentry vehicles could be parts of the original spacecraft cabin.

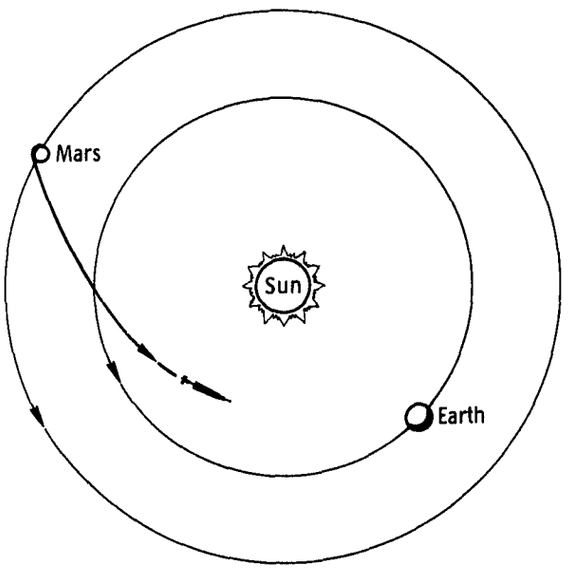


Figure 51.

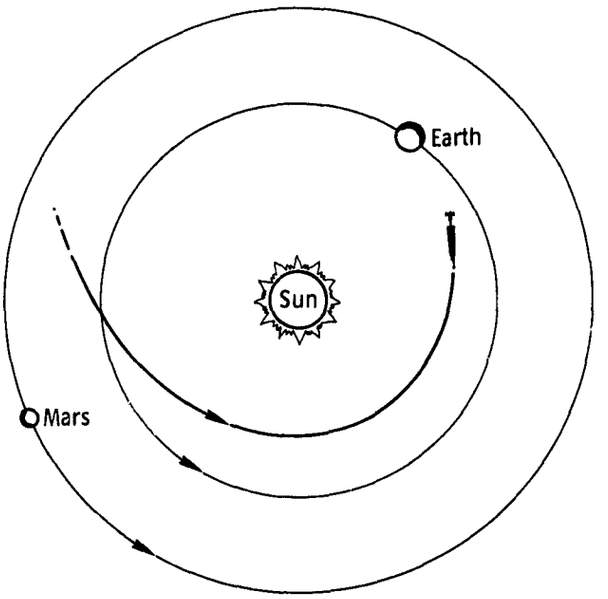


Figure 52.

High-energy radiation is one of the hazards of manned space flight. It can seriously affect the cells of the body. Many sources of radiation will surround the astronaut onboard a spacecraft: nuclear powerplants, Van Allen Belts, cosmic rays, and solar flares. Heavy shielding around the nuclear reactor is required to protect the crew. Of the sources of radiation outside the spacecraft, giant solar flares may be the most dangerous, and their occurrence cannot be predicted accurately. Radiation from solar flares consists primarily of very high-speed protons (ionized hydrogen atoms), which are thrown out from the Sun. When these protons smash into matter, intense secondary radiation is generated. The crew must be well protected against this dangerous radiation. One way to protect them is to construct very thick, heavy walls or shields to surround their cabins (fig. 49). The weight of the shielding required may be reduced by storing the propellant around the cabin. Perhaps some of the crew supplies such as water could help shield them too.

OTHER ADVANCED PROPULSION METHODS

The new propulsion methods described have all been electric propulsion systems because that is what this booklet is primarily about. Scientists and engineers, however, are also researching many other new propulsion concepts such as the nuclear-fission rocket and the nuclear-fusion rocket. The nuclear-fission rocket is more commonly known as the nuclear rocket. It has been under study for some time and enough is known about its potentialities to enable reasonably accurate performance estimates. The other rocket, the nuclear-fusion rocket, is a far more nebulous concept at present because controlled thermonuclear fusion energy has not yet been produced.

The Nuclear Rocket

Nuclear rockets, as well as electric rockets, are theoretically capable of outperforming chemical rockets for long or difficult space flights. As implied by their name, nuclear rockets use nuclear energy to produce thrust; that is, the intense heat from nuclear-fission reactors is used to heat a propellant gas that then rushes out the rear exhaust nozzle to create thrust. The rocket shown in figure 53 uses a solid-core reactor to heat the propellant. In the solid-core reactor, the hydrogen propellant picks up heat as it passes through tubes in the reactor core. A lightweight

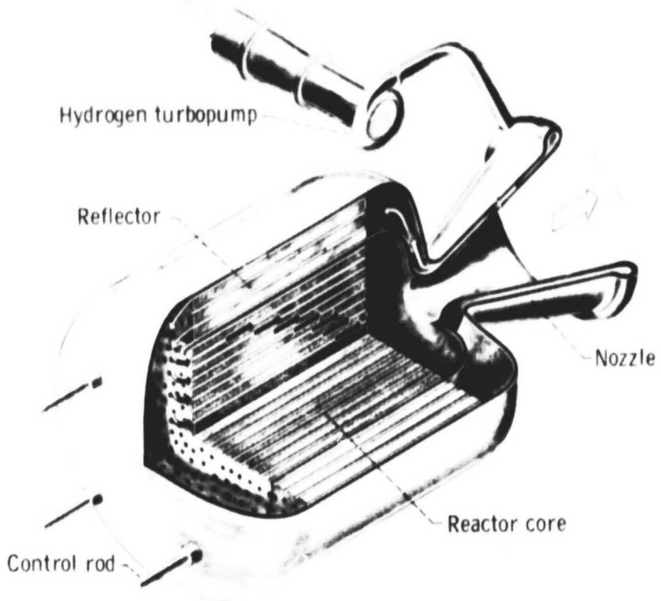


Figure 53.

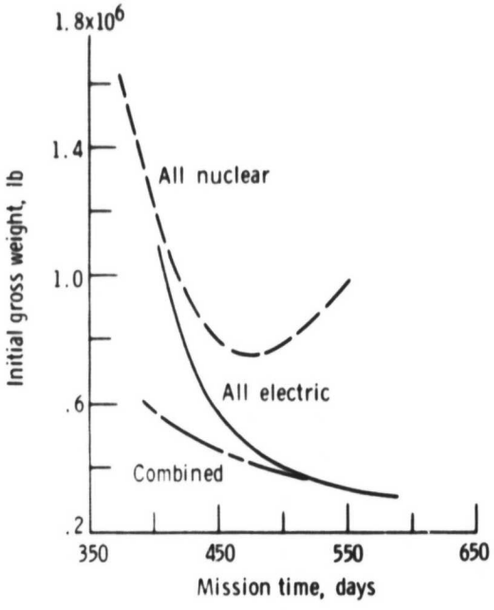


Figure 54.

propellant such as hydrogen can be used to produce an exhaust velocity twice that of the chemical rocket. However, propellant gas dissociation and component materials temperatures limit the exhaust velocity of the solid-core nuclear rocket just as they did in the chemical and electrothermal rockets.

Nuclear rockets would be very useful for making fast round trips to Mars or Venus. Nuclear rockets can produce thrust high enough to lift a rocket from the Earth's surface. The launch pad, however, would soon become radioactive. For this reason, nuclear rockets probably will be used in space after they have been boosted from Earth by a chemical rocket. The combination of high thrust and an exhaust velocity higher than that of a chemical rocket would permit a nuclear rocket to be used for a fast round trip to Mars.

Figure 54 is a comparison of the estimated initial weight needed in Earth orbit for a seven-man mission to Mars propelled from Earth orbit by a nuclear rocket, an electric rocket, and a combined system in which a nuclear rocket is used as a high-thrust stage to boost the electric rocket vehicle from its initial orbit. The comparison shows that a combined use of nuclear and electric rockets for this application can have decided weight advantages over use of either one or the other alone. This comparison is based on present-day estimates of how these propulsion systems may perform when they are finally developed. As more research and development results become available, mission studies such as this become more refined, and the

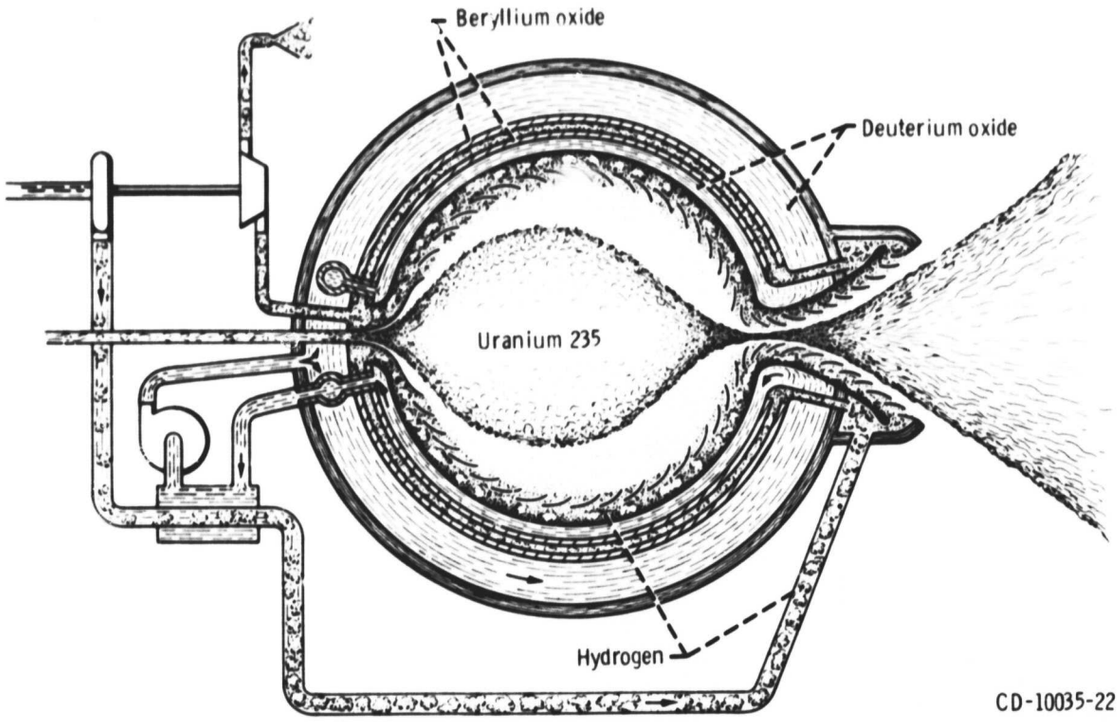


Figure 55.

comparisons and actual weight numbers become more realistic.

A less well-established nuclear-fission-rocket concept is the gas-core reactor. One proposed version of such a reactor is shown in figure 55. In the gas-core reactor, both the hydrogen propellant and the uranium fuel are injected into a chamber. Centrifugal forces and other means have been proposed to avoid excessive loss of the uranium gas. The heat generated by the fission process heats the hydrogen which then passes out through the nozzle. In addition to the problem of limiting the outflow of uranium gas through the nozzle, there are major unanswered questions regarding the feasibility of heating the propellant, the minimum workable size and pressure of the chamber, and the general practicality of developing such a rocket. Its advantage over the solid-core rocket would be the higher exhaust velocity possible because the material temperature limitation would be eliminated.

The Thermonuclear-Fusion Rocket

The basic feasibility of the thermonuclear-fusion system, another advanced propulsion concept, is not yet established. In a fusion reaction, two light isotopes

combine to form a heavier particle plus another light one. This reaction is quite the opposite of a fission reaction, in which a heavy isotope breaks into two lighter particles. In both cases, the total mass after the reaction is less than the mass before the reaction. The difference is mass that has been converted to energy, in accordance with Einstein's equation $E = mc^2$.

The fusion of a helium-3 ion with a deuterium ion (deuteron), as an example, is depicted in figure 56. This reaction, which may be the most suitable for propulsion applications, emits a helium-4 ion and a proton. The energy released by the reaction appears in the extremely high velocity of the resulting particles - about one-fifth the velocity of light for the proton and about one-twentieth the velocity of light for the helium-4 ion.

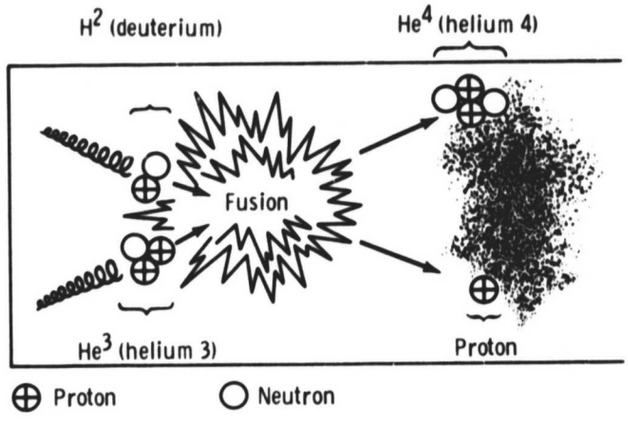


Figure 56.

For a fusion reaction to occur, the helium-3 and deuterium ions must be brought very close together. Both these ions have positive electric charges, and a large amount of energy is required to bring them together. In other words, these particles have to overcome a potential hill similar to the potential hills mentioned previously. If the particles have a high enough velocity relative to each other, they may climb the hill. This high velocity must be imparted to the plasma of fuel ions by heating it to extremely high temperatures, of the order of a billion degrees. Because of this high temperature, fusion reactors are also called thermonuclear reactors. The major obstacle in the successful development of a thermonuclear reactor lies in the yet unsolved problem of finding a way to heat a plasma of fusionable materials to the required fusion temperatures and to contain or to hold it long enough to permit the fusion energy to be released and used.

The Sun and other stars are the only known self-sustaining thermonuclear reactors. Their large masses permit very effective confinement of the fusion particles by gravitational forces. The large sizes, or volumes, of the reaction zone in the Sun permit reabsorption of much of the fusion energy released. This results in a temperature of about 20 million degrees in the Sun. The only means by which appreciable amounts of fusion energy has been released on Earth is the hydrogen bomb.

However, it has offered no key to a controlled fusion reactor. Isolated fusion events can be made to occur by impinging a high-energy beam of charged particles on a suitable target. Such experiments yield valuable scientific information but offer no means of recovering a net amount of energy.

If the future fusion reactors are as presently envisioned, they will provide three advantages of major importance to space travel. A thermonuclear propulsion system could possibly have a specific mass of about 1 kilogram per kilowatt compared with 10 kilograms per kilowatt that may be possible with advanced nuclear-electric propulsion. A controlled thermonuclear reactor is expected to be inherently safe since the amount of fuel in the reactor at any given time is so small that an explosion or a runaway reaction could not happen. Also, in contrast to fission, a fusion reactor would present little problem of disposal of radioactive products.

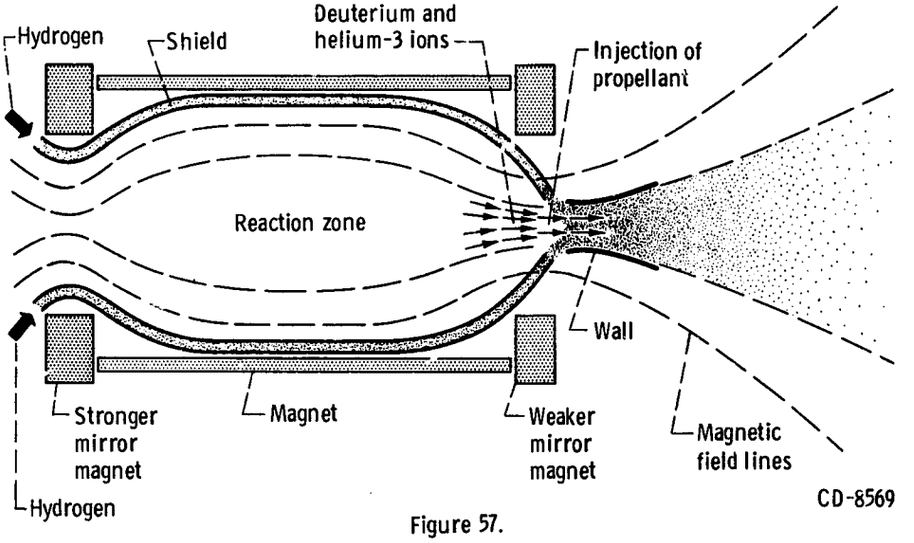
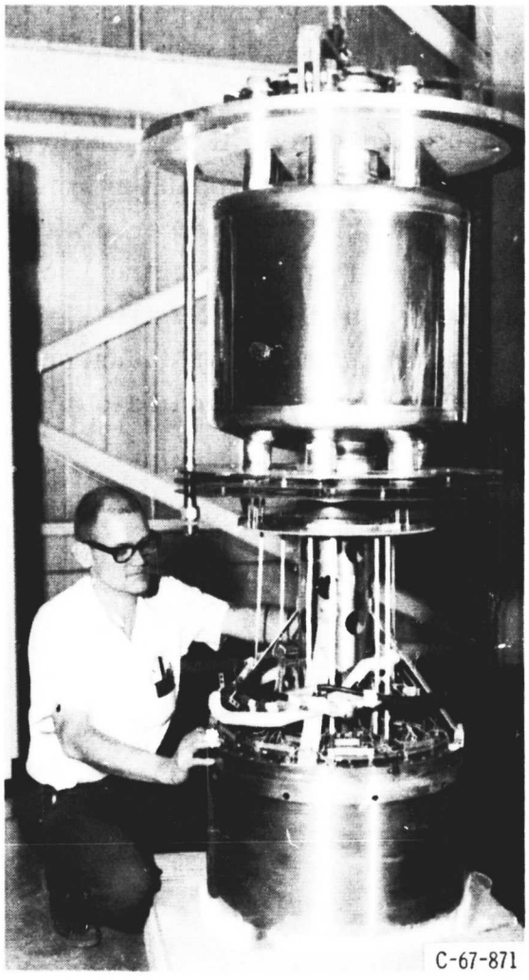


Figure 57.

One possible way of containing a high-temperature plasma is using strong magnetic fields. A simplified sketch of the cross section of a magnet configuration of interest is shown in figure 57. The dashed lines represent magnetic field lines. Charged particles are free to move along such lines, but forces in action called Lorentz forces hinder the particles from crossing those lines. Especially strong (mirror) magnets, shown at the ends in figure 57, tend to prevent the particles from escaping out the ends. One of these end magnets is slightly weaker than the other. This difference in strength results in a greater escape of high-velocity particles in



C-67-871

Figure 58.

one direction, which provides a small amount of thrust at a very high exhaust velocity.

An interesting point is that much of the relatively heavy electric-power generating equipment of the nuclear-fission - turbo-electric system is not needed. The thrust of this "thermonuclear rocket" would be very low - much lower for a given power than electric rockets - unless a propellant such as hydrogen is injected into the path of the escaping high-energy particles. The hydrogen would be ionized by the impinging reactor particles, and the resulting plasma would be accelerated rearward by transfer of energy from the escaping fusion products.

The field strengths of suitable magnets for this scheme must extend well into the 100 000 gauss (10 tesla) range. (For comparison, the strength of the Earth's magnetic field is about 1/5 gauss.) Conventional magnets used for this purpose would require enormous amounts of electric power. This power requirement could be virtually eliminated if the magnets are kept in a superconducting state. Certain materials reach a superconducting state when cooled to a temperature near absolute zero. In such a state, these materials offer no resistance to the flow of electricity. Large strides in the technology of producing superconducting magnets have been made in the last decade. (A magnet tested to 14 tesla at the NASA Lewis Research Center is shown in fig. 58.) Keeping the confining magnets in a superconducting state requires elaborate thermal shielding of the reactor. The heat that reaches the magnets must be removed by a cryoplant and then either rejected to the hydrogen propellant or to space by radiators. The scheme is depicted in figure 59.

Although controlled thermonuclear fusion has not yet been achieved, it is interesting to conjecture what a nuclear-fusion spacecraft might look like (fig. 60). For the type of manned Mars mission discussed for electric rockets, the spacecraft

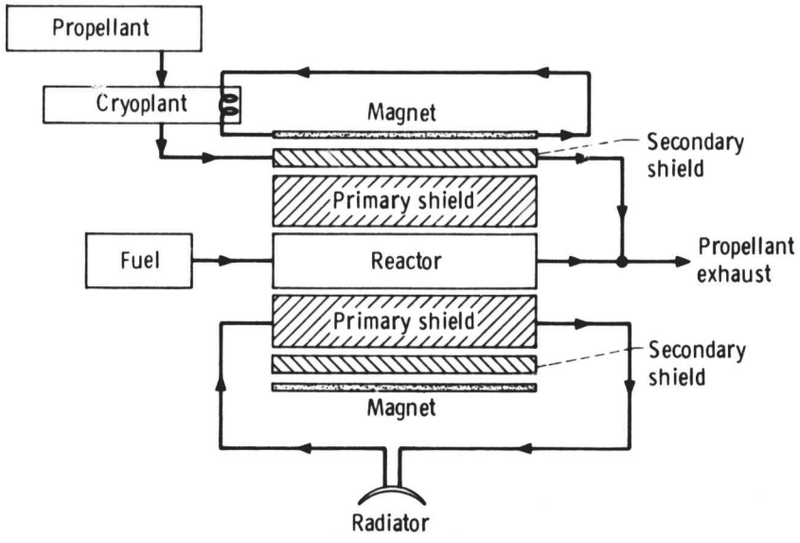


Figure 59.

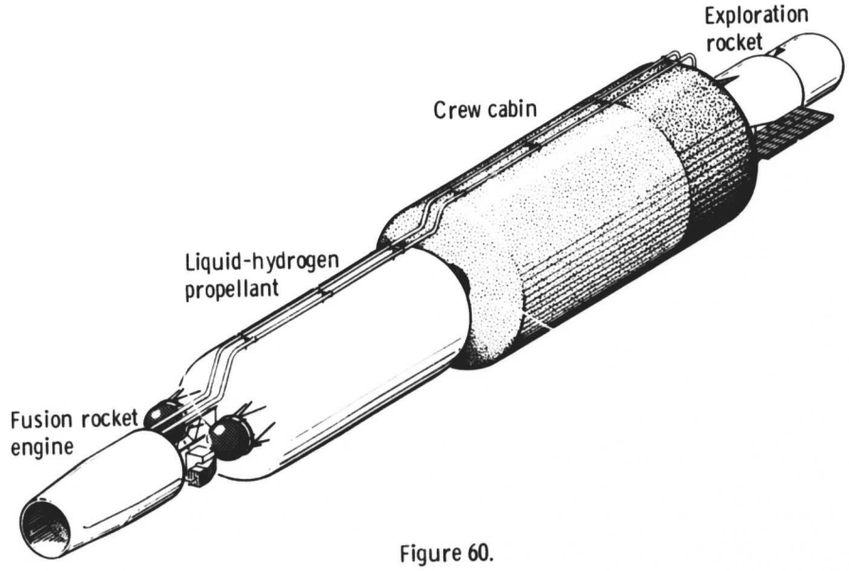


Figure 60.

would be about 150 feet long. Because of the reduced specific mass of the propulsion system, the round-trip time for a Mars exploration mission would be about 200 days instead of the 400 days estimated for an electric rocket. Or, for the same trip time as the electric rocket, a much larger payload could be carried. As for all advanced propulsion concepts, the potential advantages become greater as the distance, or difficulty, of the mission increases.

CONCLUSION

The theoretical advantage of electric propulsion for space has been recognized for more than 50 years. But this theoretical advantage could not be realized without the use of solar or nuclear energy and other technological advances. Only since 1957, the beginning of the space age, has there been the incentive to devote substantial effort to making electric propulsion a reality.

The accomplishments in this short span of time have been remarkable. The first space test of an electric thruster to determine if it would work in space took place in mid-1964. Today, electric propulsion systems are beginning to be used in practical applications. In the years to come, larger and better electric propulsion systems will appear as more challenging missions arise. Electric rockets, and the more advanced propulsion systems to follow, can provide mankind with the means to travel in and explore the farthest reaches of our solar system. They can also make the Moon and nearer planets more accessible and less costly to visit.

APPENDIX - DERIVATION OF ROCKET THRUST EQUATION

The thrust equation may be derived by applying Newton's third law of motion, which states that momentum must be conserved. In an inertial coordinate system, as shown in figure 61, and at some specific point in time, the rocket has a momentum $M\bar{U}$. A differential mass of propellant dm is ejected from the rocket with a velocity $\bar{v}$ with respect to the rocket.

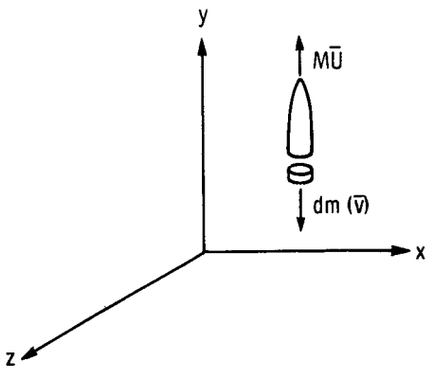


Figure 61.

By the law of conservation of momentum, the increase in the upward momentum of the rocket must equal the increase in the downward momentum of the propellant. Stated mathematically, this is

$$d(M\bar{U}) + dm(\bar{U} - \bar{v}) = 0$$

Applying differential calculus to the first term and appropriate multiplication to the second gives

$$\bar{U}\,dM + M\,d\bar{U} + \bar{U}\,dm - \bar{v}\,dm = 0$$

Since the propellant mass ejected dm originally came from the total mass of the rocket vehicle M, the change in mass of the rocket dM is equivalent to the lost mass of the propellant -dm. Thus,

$$dM = -dm$$

Because of this relation, the former equation reduces to $M\,d\bar{U} = \bar{v}\,dm$.

Applying Newton's second law of motion, $\bar{F} = M\bar{a}$, where acceleration $\bar{a}$ is equivalent to $d\bar{U}/dt$, or the change in velocity with respect to time, we find that the force exerted on the rocket, actually the thrust, is equivalent to

$$M\frac{d\bar{U}}{dt}$$

but $M\,d\bar{U} = \bar{v}\,dm$; therefore,

$$\text{Thrust} = \frac{dm}{dt}\,\bar{v}$$

or thrust equals the propellant mass rate of flow multiplied by the propellant exhaust velocity.

U.S. GOVERNMENT PRINTING OFFICE: 1969— 346738/A-7220